Estimation of Fecal Coliform Loadings to Galveston Bay

by

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Dedication

I dedicate this thesis to my mother, Lutfunessa Shahjahan. I am here today because of you and I could not thank you enough.

Acknowledgements

I acknowledge the Gulf of Mexico Program for funding this research. My gratitude goes to my advisor, Dr. David Maidment, for his guidance, support and encouragements throughout my graduate study at the University of Texas at Austin. Special thanks go to Sandra Alvarado from TCEQ for her resourcefulness and continuous support throughout this project. I would like to acknowledge Dr. Barbara Moore, Dr. George Ward, and Dr. Neal Armstrong for their technical support and assistance in various aspects of the project. Thanks to Gary Heideman at TDH, Alan Hunter at Maritime Sanitation, and Sean Ables at TCEQ for providing useful information and dataset.

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May 2003

Abstract

Estimation of Fecal Coliform Loadings to Galveston Bay

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The University of Texas at Austin, 2003

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Elevated fecal coliform concentration in Galveston Bay causes water quality impairment for oyster water use in different locations of the bay. This thesis presents analysis of bacterial monitoring data using Geographic Information System (GIS) in six impaired TCEQ Water Quality segments not meeting water quality standard for oyster water use. It is shown that several high concentration zones of bacteria exist in the study area, and the causes and effects of contamination are situated within close proximity to one another. Bacterial concentrations are log-normally distributed in the detectable range of concentration. A regional GIS model is presented for estimation of non-point fecal coliform loadings from adjacent and upstream watersheds. Non-point loadings of bacteria are estimated using relationships between land use and expected bacterial concentration. Loadings from upstream watersheds are decayed along the streams and channels entering the bay system in the model. A methodology for estimation of fecal coliform contribution from Laughing Gull population in the bay is presented. A CSTR model accounting for the total loadings and decay of bacteria in the bay gives a bay concentration of fecal coliform in the same magnitude as the observed one. Non-point loadings from upstream watersheds represented the largest contributor of fecal coliform in Galveston Bay. Retention in upstream watershed segments should significantly lower loadings to the bay segments. Estimated fecal coliform loadings from Laughing Gull populations showed significant contributions to West Bay and Lower Galveston Bay.

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CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 NEED FOR STUDY AND OBJECTIVES

Oyster fisheries in Galveston Bay hold significant importance in the economy of the area. Occasional high concentration of bacteria in the bay results in bacterial contamination of the oysters and, thus, subjects the oyster-consuming public to health risks and consequently hampers oyster harvesting in the area. In order to protect the oyster-consuming public from health risks, parts of Galveston Bay with observed high fecal coliform concentrations or reported illnesses are closed for oyster harvesting. To address this problem, water quality standards are set for waterbodies to be suitable for oyster harvesting and programs are launched in order to attain the specified water quality criteria in waterbodies subjected to oyster harvesting.

The Galveston Bay Oyster Water project is intended to provide technical support to the Texas Commission on Environmental Quality (TCEQ) Total Maximum Daily Load Program for the development of total maximum daily loads (TMDL). The project is necessitated by TCEQ's effort to assess the causes and sources of water quality impairments in 14 coastal segments identified in the Draft 2002 Texas Water Quality Inventory and 303(d) List as not having acceptable water quality to meet the oyster water use. A waterbody is 'impaired' when it does not meet water quality standards set by the state for a designated use and placed in the 303(d) list.

The research objective of the Galveston Bay Oyster Water project is to compile and analyze existing data and information in order to understand the problem, identify the potential sources of bacterial contamination, develop a model to quantify and allocate contaminant loadings, and estimate the relative magnitude of loadings from different sources in each bay segment.

1.1.2 Study Area

The geographic focus of the Galveston Bay Oyster Water project is six impaired segments in the upper Texas Coast - Upper Galveston Bay, Trinity Bay, East Bay, West Bay, Chocolate Bay and Lower Galveston Bay (Figure 1.1.2).

The Galveston Bay system is a complex ecosystem that provides natural resources, ecological services, recreational opportunities, transportation links, economic benefits and aesthetic rewards. The Bay is home to a large number of living species. Fish and wildlife resources provide some of the Bay's greatest economic, recreational and aesthetic assets.

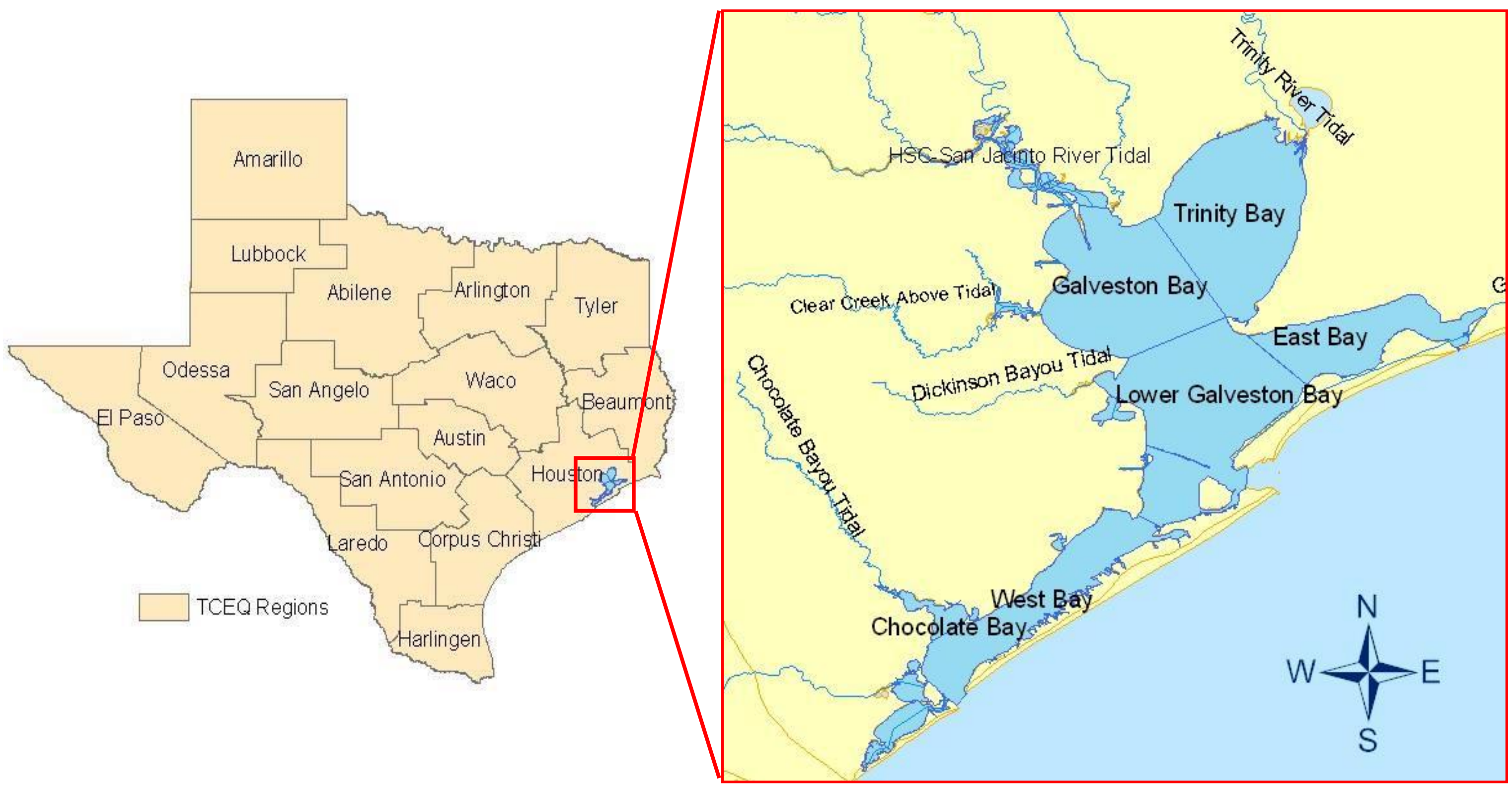


Figure 1.1.1: Location of Study Area in the State of Texas

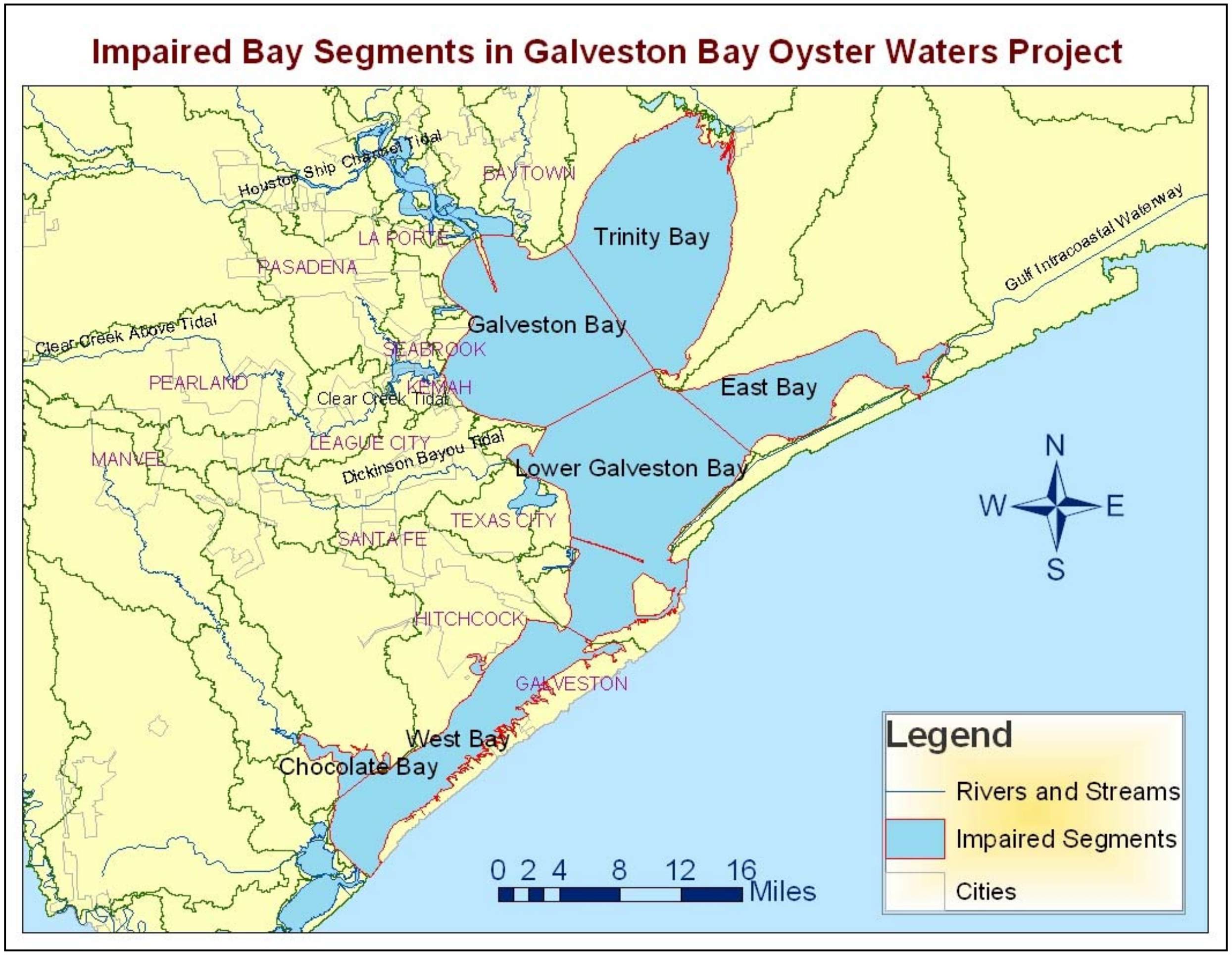


Figure 1.1.2: Impaired Bay Segments in Galveston Bay Oyster Water project

1.1.2.1 Description of Impaired Segments

The six impaired segments of Galveston Bay have a total area of 519.1 square miles (1344.5 square kilometers). Contiguous land use around Galveston Bay ranges from wetlands and undisturbed pasture to agricultural use to urban development.

Upper Galveston Bay (Segment 2421) has a total area of 115.5 square miles (299.1 square kilometers). It is bordered by densely populated cities including Baytown, La Porte, Seabrook, Kemah and League City on the west. Upper Galveston bay receives the outflow of the San Jacinto River and much of the local drainage from the City of Houston via the Houston Ship Channel. The port of Houston and the cities of Pasadena, Deer Park and Baytown lie along the Houston Ship Channel and represent large population centers and heavily industrialized areas. The Houston Ship Channel then bisects Galveston Bay from north to south. The channel is responsible for bringing significant ship and barge traffic through the entire length of the bay system (TDH 2000).

Trinity Bay (Segment 2422) has a total area of 122.6 square miles (317.5 square kilometers) and is bordered mostly by grazing land and small communities. Trinity Bay receives the outflow from the Trinity River. The Trinity River enters the Galveston Bay in the eastern portion of Trinity Bay (TDH 2000).

East Bay (Segment 2423) has a total area of 57.5 square miles (148.9 square kilometers). East Bay lies landward of Bolivar Peninsula and receives inflow from Oyster Bayou and other runoff from Chambers County. East Bay is a shallow arm of Galveston Bay and is bordered on the north by sparsely populated Smith Point, livestock grazing land and the Anahuac National Wildlife Refuge. Bolivar Peninsula, the southern shore of East Bay, is rich in wetland, marshes and bird populations.

West Bay (Segment 2424) and Chocolate bay (Segment 2432) have total areas of 75.4 and 8.1 square miles (148.9 and 21.1 square kilometers) respectively. The two segments include bodies of water southwest of the Texas City Dike, South to Brazoria National Wildlife Refuge. West Bay is situated landward of Galveston Island, and receives runoff from Chocolate Bayou, Mustang Bayou and other local bayous. It is a shallow, lagoon-like arm of the Galveston bay system. It is bordered on the south by Galveston Island. The northern shore of West Bay is bisected by the Gulf Intracoastal Waterway.

Lower Galveston Bay (Segment 2439) has a total area of 140 square miles (362.4 square kilometers). It is bordered by Upper Galveston Bay in the north, Texas City and West Bay on the west and East Bay in the east. In the south it is bordered by Galveston Island and Bolivar Peninsula, and it has an opening to the Gulf of Mexico.

1.1.2.2 Tidal Inlets to the Galveston Bay system

There are three tidal inlets to the Galveston Bay system; two of these are of major importance with regard to water exchanged with the Gulf of Mexico. Bolivar Roads (Figure 1.1.3), located between Galveston Island and Bolivar Peninsula, accounts for the majority of the tidal exchange between the bay and the Gulf of Mexico. San Luis Pass, between the western end of Galveston Island and Follets Island, is a natural inlet that provides a lesser amount of bay's tidal exchange. Rollover Pass is a man-made cut through Bolivar Peninsula that provides minor tidal exchange between the Gulf of Mexico and the East Bay (Lester et al 2002).

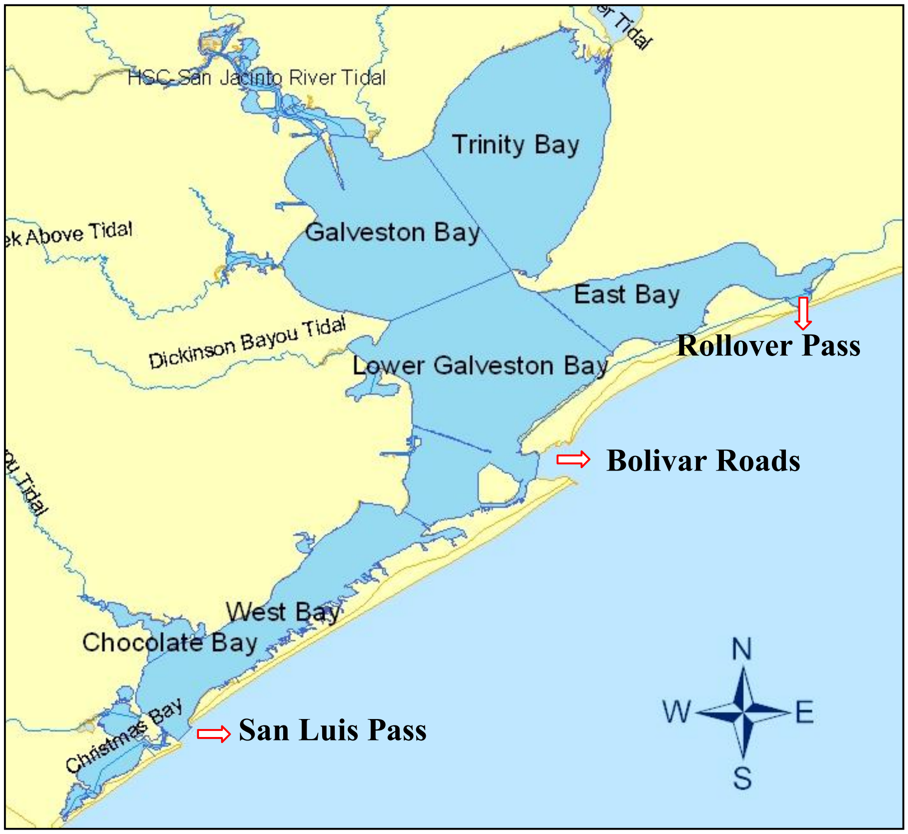


Figure 1.1.3: Location of Tidal Inlets to Galveston Bay

1.1.2.3 Study Area Watershed

Galveston Bay is the receiving catchments for the San Jacinto River Basin, Trinity-San Jacinto Coastal Basin, San Jacinto-Brazos Coastal Basin, Neches-Trinity Coastal Basin and the Trinity River Basin. The watershed area that drains to these bay segments has a total area of approximately 8556 square miles (22160 square kilometers) and includes 51 Texas Commission on Environmental Quality (TCEQ) water quality management segments.

The study area watershed covers land area in Brazoria, Galveston, Jefferson, Chambers, Harris, Liberty, Montgomery, Walker, San Jacinto, Polk, Fort Bend, Waller, Grimes, and Hardin counties. Houston, Liberty, Pasadena, League City, Texas City, Galveston, Beaumont, Port Arthur, Baytown, Seabrook, Hitchcock, Missouri City, Humble, Cleveland, Shepherd and Livingston are some major cities located in the project watershed.

Description of derivation of project watershed area is presented in chapter 3 of this report. The study area watershed for Galveston bay oyster water project is presented in Figure 1.1.4.

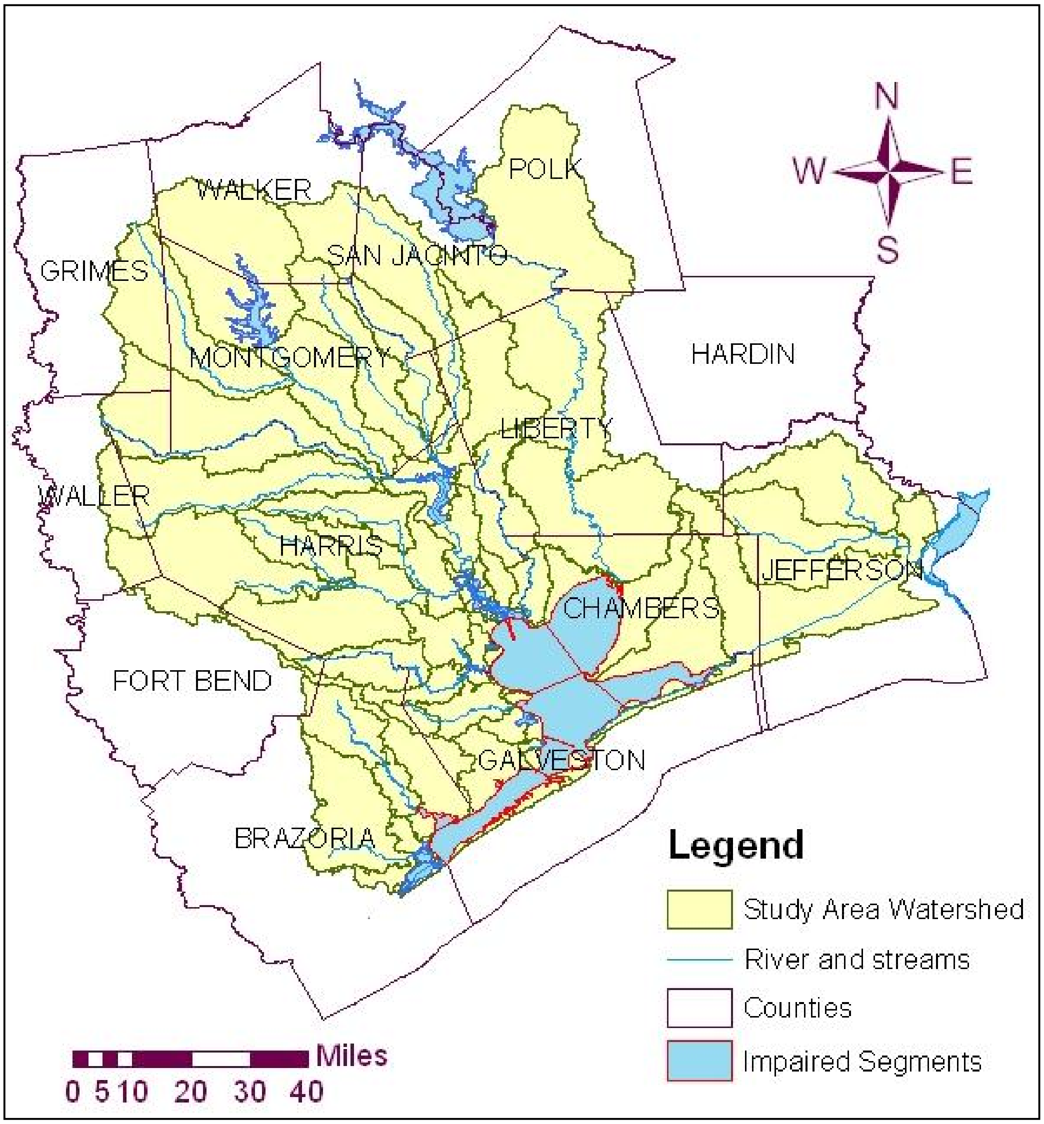


Figure 1.1.4: Study Area Watershed for Galveston Bay Oyster Water project

1.1.4 OYSTER REEFS

The oyster fishery in the Galveston Bay plays a very important role in the local economy. The commercial value of oyster species in the bay is well established with a history of over one hundred years. Oysters are harvested from both public reefs and private oyster leases in the bay. Figure 1.1.5 shows the locations of oyster reefs in Galveston Bay system.

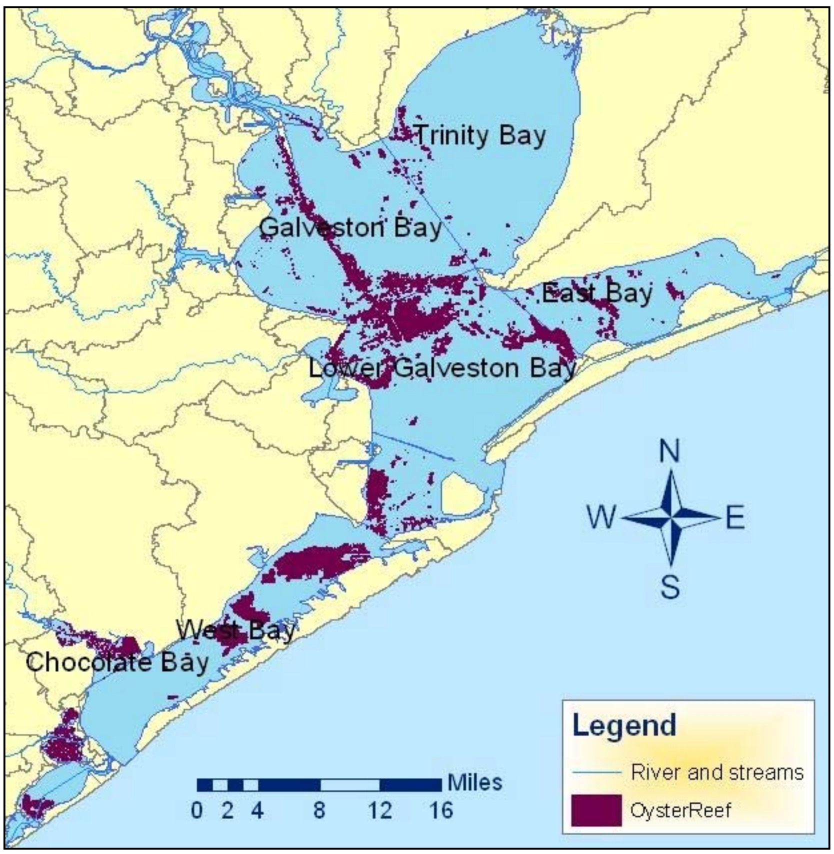


Figure 1.1.5: Location of Oyster Reefs in Galveston Bay

Between 1994 and 1998, the annual commercial harvest of oyster from Galveston Bay averaged close to four million pounds. For the same period, the annual value of oysters caught in Galveston Bay averaged more than eight million dollars (Lester et al. 2002). In addition to its commercial value, oysters also serve an important ecological role as filter-feeders in the estuary. The volume of water filtered per hour in approximately 1500 times the volume of their body. A large, healthy oyster population is able to filter large volumes of bay water, and may, therefore, influence conditions such as water clarity and phytoplankton abundance (Lester et al. 2002). Oysters create reef habitats utilized by many other species and serve as an important indicator of the overall health of bay ecosystem.

1.2 Total Maximum Daily Load Program

1.2.1 DEFINITION

The TMDL is the total amount of a pollutant a water body can assimilate and still meet water quality standards. The term also refers to the assessment necessary to establish an acceptable pollutant load for an impaired water body. Once the TMDL or the allowable load is determined, it is allocated to contributing point, non-point, and natural background sources of pollution in the watershed and a reduction in load by each contributing source is determined (TNRCC, 1999). A TMDL is a tool for implementing state water quality standards. The TMDL provides the foundation for establishing an implementation plan to restore and maintain beneficial uses (TNRCC, 1999).

1.2.2 TMDL REQUIREMENTS FOR OYSTER WATER USE

According to *Chapter 307: Texas Surface Water Quality Standards* (TNRCC 2000), following are the criteria for fecal coliform/ E.coli for the oyster water use in the state of Texas:

- Median fecal coliform concentration in bay and gulf waters shall not exceed 14 colonies per 100 ml, with not more than 10% of all samples exceeding 43 colonies per 100 ml.
- Oyster waters should be maintained so that concentrations of toxic materials do not cause edible species of clams, oysters, and mussels to exceed accepted guidelines for the protection of public health.
- Guidelines are provided by U. S. Food and Drug Administration Action Levels for molluscan shellfish.
- A 1,000 foot buffer zone, measured from the shoreline at ordinary high tide, is established for all bay and gulf waters, except those contained in river or coastal basins.

United States Environmental Protection Authority (USEPA) recommends waters quality criteria for shellfish harvesting water based on both total coliform and fecal coliform. Water quality criteria for shellfish harvesting water currently recommended by United States Environmental Protection Authority are presented in Table 1.2.1 (EPA protocol, 2001).

Pathogens Evaluated	Water Quality Criteria
Total Coliform	Geometric mean of 70 MPN per 100 ml, with not more than 10 percent of the samples taken during any 30-day period exceeding 230 MPN per 100 ml.
Fecal Coliform	Median concentration should not exceed 14 MPN per 100 ml, with not more than 10 percent of the samples taken during any 30-day period exceeding 43 MPN per 100 ml.

Table 1.2.1: Currently recommended water quality criteria by USEPA (Source: USEPA, 1976)

1.3 Potential Sources of Contamination

The point sources of pollution in the impaired segments of Galveston Bay are wastewater treatment plants, identifiable sewer overflows and sludge application fields. The non-point sources of pollution affecting the bay are from storm-water runoff, aging septic systems with potential to leach fecal pollution through subsurface flows, marinas and boats with inadequate sewage collection systems and bird droppings. Sediments may act as a repository for fecal coliform, but the role of sediment as a source of fecal coliform is ambiguous of this time. Even though re-growth of bacteria in sediment has been suggested in some studies, it has not been confirmed as a source of bacteria in actual estuarine or marine environments. Rivers and streams entering the estuary receive both point and non-point pollution as they drain the watersheds.

1.4 Outline of Thesis

Chapter 1 of this report outlines the background, objectives and scope of the project. Description of the project study area is also presented in this chapter. Chapter 2 reviews published literature on bacteria, sampling methods and decay rate for bacteria, previous studies conducted to characterize loadings to Galveston Bay, and shellfish classification administered by Texas Department of Health (TDH) in Galveston Bay.

Chapter 3 documents the descriptions of various dataset used in this project. Description of monitoring dataset and required geospatial data layers for estimation of loadings are presented in section one and section two of this chapter respectively. Chapter 4 presents the spatial and statistical analysis of fecal coliform monitoring data.

Chapter 5 describes estimation of fecal coliform loadings from different sources, estimation of total loadings and a simplified water quality model. Section 1 of Chapter 5 discusses development of an ArcHydro Geodatabase for the Galveston Bay system. Section 2 presents estimation of non-point loadings from watersheds adjacent to impaired segments.

Section 3 presents a methodology to decay non-point loadings from upstream watersheds along the streams and estimation of loadings from upstream watersheds. Methodology to account for retention time in Lake Houston is also presented in this section.

Section 4 presents estimation of fecal coliform loadings from Lake Houston and Lake Livingston. Section 5 discusses loadings from wastewater treatment plant bypasses, septic systems and boat traffic.

Section 6 discusses contribution of fecal coliform from birds in the Galveston Bay. Estimation of fecal coliform loadings to study area from laughing gull, the most abundant species of bird in Galveston Bay, is also presented.

Section 7 presents total loadings as sum of loadings from above mentioned sources. A Continuous Stirred Tank Model (CSTR) for the Galveston Bay segments is presented in Section 8 of Chapter 5.

Chapter 6 presents the results from estimation of loadings and Continuous Stirred Tank Reactor (CSTR) modeling. Chapter 7 discusses the conclusions and recommendations of the project.

CHAPTER 2: LITERATURE REVIEW

2.1 Bacteria

2.1.1 TOTAL COLIFORM AND FECAL COLIFORM

The coliform bacteria group consists of several genera of bacteria belonging to the family *enterobacteriaceae*. Some of these bacteria occur naturally in the intestinal tracts of animals and humans, as well as others in soil and in fresh or marine waters and could be pathogenic to a variety of specific hosts (EPA protocol 2001). By definition, the total coliform (TC) bacterial group is a large group of aerobic or facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hr at 35^0C (Thomann & Mueller 1987, Chapra 1997).

A specific subgroup of the total coliform group is the fecal coliform bacteria, the most common member being *Escherichia coli*. Fecal coliform bacteria are present in large numbers in the feces and intestinal tracts of humans and other warm-blooded animals. Each human produces approximately 2×10^9 organisms of fecal coliform bacteria per day (Metcalf & Eddy 1991). Fecal Coliform organisms may be separated from the total coliform group by their ability to grow at elevated temperatures and are associated only with the fecal material of warm-blooded animals. Fecal coliform is approximately 20% of total coliform (USEPA 2001).

E. coli (Escherichia coli), a subgroup of fecal coliform bacteria, is a part of normal intestinal flora in humans and animals and is, therefore, a direct indicator of fecal contamination in a waterbody (USEPA 2001).

The presence of fecal coliform bacteria in aquatic environments indicates that the aquatic environment has been contaminated with the fecal material of humans or other animals. Fecal coliform bacteria can enter bodies of water through direct discharge of waste from mammals and birds, from agricultural and storm runoff, and from untreated human sewage. Individual home septic tanks can become overloaded and allow human wastes to flow into drainage ditches and nearby waters. Agricultural practices such as allowing animal wastes to wash into nearby streams during the rainy season, spreading manure on fields during rainy periods, and allowing livestock watering in streams can all contribute to fecal coliform contamination of streams and waterbodies.

Shellfish species reside in estuaries where fecal microbes can enter their tissues as they feed by filtering water to gather nutrients. Properly cooked shellfish may pose no threat of infectious disease, but oysters, which are frequently consumed raw, may hold potentially pathogenic bacteria or viruses for weeks or months before harvest (McGinley 2000).

2.1.2 FECAL COLIFORM SAMPLING METHOD

Two common methods applied for measuring bacterial concentration in aquatic environment are the most probable number (MPN) method and the membrane filtration method.

2.1.2.1 MPN Method

The multiple- tube fermentation technique is more commonly known as the MPN method. The MPN procedure involves placing liquid samples into fermentation tubes containing a specified culture broth containing the disaccharide, lactose. The inoculated tubes are incubated at 35^0C for 24 hours. The appearance of gas, indicating fermentative growth of bacteria using lactose as a carbon source, is interpreted as a positive presumptive test for total coliform bacteria. Positive tubes in this presumptive test are confirmed as *fecal coliform* by transferring a small volume from all positive total coliform tubes into a selective differential medium [i.e., a culture medium that suppresses the growth of non-fecal coliforms]; these tubes are placed at a temperature of 44.5^0C and scored for gas production at 24 hours. (APHA 1999).

The number of tubes producing gas is converted to express the results of the test as the Most-Probable-Number (MPN) per 100 mL of water, a statistical estimation of the number of coliform bacteria that would give the results shown by laboratory examination. The MPN is based on the application of the Poisson distribution for extreme values to the analysis of the number of positive and negative results obtained when testing multiple portions of equal volume and in portions constituting a geometric series (Metcalf and Eddy 1991). The MPN provides a statistical probability number, not an actual enumeration and has a 23 percent positive bias associated with it (EPA protocol 2001).

2.1.2.2 Membrane Filtration Method

The Membrane Filtration Technique is an Environmental Protection Agency (EPA) certified method for testing water for coliform bacteria. In this technique, a measured amount of sample is filtered through a membrane with a nominal pore size of 0.45 μm. Bacteria are retained on the membrane and the filter is placed on a surface of selective agar medium and incubated at 44.5^0C for 24 hours. When using m-FC medium, blue colonies formed by the growth of the bacterial cells are counted as fecal coliform using low magnification as necessary. The membrane filter technique thus provides an estimate of the number of coliform bacteria that form colonies when cultured (colony-forming units or CFU per 100 mL). The count is considered to be an estimate since some of the colonies can be from more than one bacterium (APHA 1999).

The membrane filter (MF) technique is highly reproductible, can be used to test relatively large volumes of sample, and yields numerical results more rapidly than the multiple-tube procedure. However, the membrane filter technique has limitations, particularly when testing waters with high turbidity or noncoliform (background) bacteria. Waters with high turbidity or noncoliform (background) bacteria levels can interfere with the membrane filtration procedure by clogging the filter or suppressing coliform growth respectively. .For such waters or when the membrane filter technique has not been used previously, it is desirable to conduct parallel tests with the multiple-tube fermentation technique to demonstrate applicability and comparability (EPA protocol 2001).

2.1.2.3 Comparing Results from MPN Method and Membrane Filtration Method

Prior to the adoption of the membrane filtration (MF) method as a "standard method" for the enumeration of coliform bacteria in environmental waters, comparisons were made in different laboratories to assess the comparability of this newer technique against the well-established multiple-tube fermentation procedure (MPN method). The results of coliform counts by the MF and MPN procedures were compared on the basis of the 95% confidence limits of the most probable number value. When MF coliform values fell within the 95% confidence limits, they were considered to be in agreement with those determined by the MPN method applied to the same split sample. Over a one year period, nine participating laboratories collected water samples representing raw water sources, finished waters and other sources including wells, rivers and streams. In the committee report describing the results of this comparative testing, Kabler (1954) concluded that the two procedures do not measure precisely the same group of bacteria. However, in testing 1,706 samples representing a variety of water sources, results for coliform bacteria were in agreement for 1,260 of these samples (73.8%). In testing freshwater surface samples (rivers, reservoirs, and lakes), agreement ranged from 60% to 88%.

Data reported also show that within each participating laboratory, agreement between MF and MPN procedures applied to the same water sample was variable. Based on three separate testing periods beginning in July, 1952 through June, 1953, MF/MPN agreement within individual participating laboratories ranged from 59% agreement to 93% agreement with averages across all labs of 68%, 79% and 75%. (Kabler, 1954). In order to compare bacterial values detected by either the MPN or the MF method, each testing laboratory must conduct parallel MF and MPN testing on split samples representing each water type being monitored. Otherwise, it is not possible to estimate the degree of agreement between coliform values measured by these techniques.

Completion of either the MPN or MF methods to detect the presence of coliform bacteria requires not only technical expertise, but also judgment based on training and experience. Values reported as coliform bacteria using the MF method generally have a higher verification rate; i.e., when coliform colonies are subjected to further identification of individual bacteria, they are verified as members of the coliform group more frequently. In analyzing 91 samples representing a variety of surface waters and sewage, Geldreich and associates (1967), reported that overall the MF method had a higher rate of coliform verification (78.1%) than the MPN confirmed test (70.3%). However, even this varied depending upon the source of the water sample, with MPN-detected coliform having higher percentage verification when isolates were recovered from sewage and river samples.

In general, the results obtained from the two different methods are in same order of magnitude. However, an exact mach of fecal coliform count obtained from the two sampling method for is not expectable.

2.1.3 DECAY RATE OF FECAL COLIFORM BACTERIA

The die off rate of indicator bacteria is considered to be best represented by a first-order equation. The overall first-order decay rate of bacteria, K_B (day^{-1}) can be written as (Thomann and Mueller 1987)

$$K_B = K_{B1} + K_{BL} + K_{BS} - K_a \qquad (2.1.1)$$

where K_{B1} = basic death rate as a function of temperature, salinity, predation

K_{BL} = death rate due to sunlight

K_{BS} = net loss (gain) due to settling *(resuspension)*

K_a = aftergrowth rate

However, in practice an alternate manner of expressing the overall decay rate is widely used to describe the decline of bacteria. The alternate expression is the time to obtain 90% mortality or loss of the original number of bacteria assuming a first order loss (Thomann and Mueller 1987).

The 90% mortality time, t_{90}, is given by equation 2.1.2 and 2.1.3 (Thomann and Mueller 1987).

$$0.10 = \exp(-K_B t_{90}) \qquad (2.1.2)$$

or $$\ln(0.1) = -K_B t_{90}$$

or $$-2.3026 = -K_B t_{90}$$

or $$t_{90} = \frac{2.3}{K_B} \qquad (2.1.3)$$

For TMDL study, die-off equations may be applied sequentially to a series of stream reaches with point source inputs (USEPA Protocol 2001). Typical fecal coliform decay rates found in published literature are presented in Table2.1.1.

Table 2.1.1: Fecal Coliform Die-Off Rates[a]

Medium	$T_{90(d)}$	K_B	Reference
Freshwater			
Storm water, 10°C	9.5	0.2	Geldreich et al., 1968
Storm water, 20°C	1.7	1.4	Geldreich et al., 1968
WSP[b] effluent	1.5	1.5	Mezrioui et al., 1995
River water, 20°C	1.5	1.5	Bogosian et al., 1996
Estuarine			
WSP + seawater [1:10], {'gradual' salinity increase}	3.2	0.7	Mezrioui et al., 1995
WSP + seawater [1:10], {'rapid' salinity increase}	1.7	1.4	Mezrioui et al., 1995
Seawater			
Sterilized seawater, 20°C	6	0.4	Bogosian et al., 1996
Seawater (lab), 6°C	5.5	0.4	Wait & Sobsey, 2001
Seawater (lab), 12°C	3.7	0.6	Wait & Sobsey, 2001
Seawater (lab), 20°C	3.3	0.7	Wait & Sobsey, 2001
Seawater (lab), 28°C	1.3	1.8	Wait & Sobsey, 2001
Seawater, *in situ* @ 3m	2.5	0.9	Wait & Sobsey, 2001
Seawater, *in situ* @ 10m	2.1	1.1	Wait & Sobsey, 2001

2.1.3 FACTORS AFFECTING DECAY RATE OF FECAL COLIFORM

Many environmental parameters influence the die-off, fate and distribution of fecal indicator bacteria in waters. The major factors that influence the kinetic behavior of coliform after discharge to a water body are sunlight, temperature,

[a] with the exception of Wait & Sobsey, 2001, $T_{90(d)}$ and K_B values are estimated from published tables or figures within the cited references using the formula: $T_{90(d)} = 2.3/K_B$ [US EPA, 2001]

salinity, pH, production of antimicrobial compounds by other microbes, and predation by protozoa (Thoman and Mueller 1987).

2.2 Water Quality Parameters in Galveston Bay

2.2.1 TEMPERATURE

Average summer water temperature (collected for July and August of every year) in Galveston Bay ranges from 28^0C to 31^0C. Average water temperature during winter months (December through January) ranges from 9^0C to 18^0C. This information is based on data collected from all reporting stations in Galveston Bay between 5 a.m. and 10 a.m. at 0.3 meter depth during 1969 to 1999 (Lester et al. 2002).

Galveston Bay exhibits homogeneous water temperatures with little vertical stratification due to its shallow depths and mixing by wind. Seasonal change is the principal source of variation in water temperature in the bay (Lester et al. 2002).

2.2.2 SALINITY

Salinity is determined by intermixing of fresh and oceanic waters in estuarine environments and is an excellent indicator of circulation and flushing in an estuary. Salinity is also one of the controlling factors of fecal coliform decay rate.

Galveston Bay exhibits an increasing salinity gradient from upper to lower bay. Salinity measured near the principal points of inflow such as the Trinity River may be as low as three parts per thousand (ppt) while values are as high as 30 ppt may occur at the Gulf inlet. Under most conditions, the upper half of the bay, above Smith and Eagle Points, exhibit salinities that are less than 10 ppt while higher salinities are common in the lower base. The bay water shows slight vertical salinity stratification, generally averaging less than 0.6 ppt/meter (Lester et al. 2002).

Galveston Bay experiences lower average salinity as it receives urban watershed runoff in addition to San Jacinto River inflow. East Bay and West Bay exhibit higher salinity caused by high salinity Gulf water entering the bays through the tidal passes. A prominent ridge of high salinity water occurs in East Bay between Hanna Reef and Bolivar Peninsula. The highest average baywide salinity (15 ppt) occurs in West Bay due to the influence of both more saline Gulf waters and the presence of the Texas City Dike (Lester et al. 2002).

2.2.3 pH

pH is the negative logarithm of concentration of [H+] in water, and it indicates the acidity or alkalinity of aquatic environment. Various dissolved compounds including salts and gases affect pH in water. Seawater has a higher pH (is more alkaline) than freshwater due to the concentration of bicarbonate ions in seawater. In coastal environments, pH exhibits low variability due to the high buffering capacity of seawater (Lester et al. 2002).

The average pH in Galveston Bay is approximately 7.7. Some extreme pH values are recorded in Galveston Bay system. Values greater than 9 have been recorded in the Houston Ship Channel, Trinity Bay, Clear Lake, Armand Bayou and Taylor Bayou. pH values less than 6 are recorded in deep water in the the Houston Ship Channel and Dickinson Bayou (Lester et al. 2002).

2.3 Sources of Fecal Coliform Loadings to Galveston Bay

There are several Galveston Bay Estuary Program studies addressing the issues of fecal loading to Galveston Bay from various sources. A Galveston Bay Estuary Program (GBEP) study conducted by Newell et. al. (1992) investigates and characterizes non-point loadings of different contaminates to Galveston Bay including fecal coliform. A separate GBEP study (Jensen and Su 1992) attempted to analyze and quantify contributions of fecal coliform to Galveston Bay from a range of sources including permitted wastewater discharges; wastewater collection system leaks, overflows and excursions; partially treated wastewater from failed septic systems; and runoff from watershed areas. A study conducted by Armstrong and Ward (1993) characterized point sources of loadings to Galveston Bay based on permit data. Guillen et. al. (1994) estimated loadings from partially treated domestic wastewater in the bay.

2.2.1 POINT SOURCES

The loadings considered in the point sources study (Armstrong and Ward, 1993) are from permitted wastewater discharges and from major tributaries entering the bay. The latter category included materials leaving Lake Livingston and Lake Houston over their spillways. Flows associated with the loadings include actual average industrial flow and municipal flow. Much of the industrial flow in Upper Galveston Bay and Lower Galveston Bay is cooling water contributed by Houston Lighting and Power generating stations with smaller amounts from other industries. All of the industrial flow in Trinity Bay is contributed from cooling water. The study indicated highest fecal coliform concentration in the Houston Ship Channel Tidal (Segment 1006) and Houston Ship Channel/Buffalo Bayou Tidal (Segment 1007). Estimated non-point loadings and associated flow for the impaired segments are presented in Table 2.3.1.

Table 2.3.1: Point Sources Loadings to the impaired segments (Armstrong and Ward, 1993)

	Industrial Flow (m^3/yr)	Municipal Flow (m^3/yr)	Total Flow (m^3/yr)	Fecal Coliform Point Load (cfu/yr)
Upper Galveston Bay (2421)	1.64E+09	8.02E+06	1.65E+09	1.73E+13
Trinity Bay (2422)	1.58E+09	7.37E+05	1.58E+09	1.47E+12
East Bay (2423)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
West Bay (2424)	3.29E+03	7.71E+06	7.72E+06	1.54E+13
Chocolate Bay (2432)	0.00E+00	3.73E+06	3.73E+06	7.46E+12
Lower Galveston Bay (2439)	1.26E+08	5.44E+06	1.31E+08	2.63E+13

At present, there are no permitted discharges of fecal coliform from the wastewater treatment plants to the impaired segments (Personal communication, Sandra Alvarado, December 2002). Permittees are required to disinfect effluent prior to discharging. However, this may not be the case during the high flow situation and wet weather due to overflow of the wastewater treatment plant capacity.

2.2.2 Non-point Sources

Studies (Newell et al. 1992, Armstrong and Ward 1993, Jensen and Su 1992, Guillen et al. 1994) suggest that the principal source of fecal coliform bacteria to Galveston Bay is runoff from upland area, with urbanized area being one of the major components. It is speculated that part of the reason fecal coliform levels are high in urbanized areas is due to the contribution from sewer leaks and overflows. However, even when the collection systems are not leaking, urban area runoff generally has high fecal coliform levels, and runoff occurs in much greater volume than sewage leaks or overflows (Lester et al. 2002). Newell et al. (1992) found a total of 335×10^{15} colonies of fecal coliform runoff to Galveston Bay in an average year.

2.2.3 Wastewater Treatment Plant Bypass and Septic System

Jensen and Su (1992) concludes neither septic systems along the bay’s shoreline nor permitted point source discharges are major contributors of fecal coliform bacteria to the bay as a whole. However, both septic systems and discharges can be important contributors of bacteria locally.

Guillen et. al. (1994) investigates the potential magnitude and severity of partially treated effluent loading into Galveston Bay system. The study estimated fecal coliform loading from faulty collection system bypasses is 0.144×10^{15} cfu and loadings from septic tank is 0.000027×10^{15} cfu annually. These results conform with Jensen and Su (1992) in concluding that fecal coliform loadings from bypasses and septic tanks are not significant compared to other sources. However, loadings into specific water bodies have had severe localized impact. The study (Guillen et al. 1994) also mentions that due to the lack of good monitoring data is difficult to ascertain the exact impacts on water quality.

The estimation of loadings calculated by Guillen et al. (1994) from failing septic systems was based on reported malfunction which the authors suspected greatly underestimated the true incidence of malfunctions. 1992 data for Harris, Galveston, Chambers and Brazoria counties were used for estimation.

Under the same study (Guillen et al. 1994), bypass / overflow reports were retrieved for all the waste water treatment plant (WWTP) under review for 1991 to 1992 for characterization of collection system and treatment plant bypasses. Four hundred twenty-six (426) of the permitted discharges were examined for their bypass contributions in Harris, Galveston, Brazoria, Chambers, Liberty, and

Fort Bend counties. The estimation was then adjusted to 100% of the permits to make the final estimation of discharge from bypasses.

2.2.4 Loadings from Birds

Several papers (Rifai & Jensen 2001, USEPA protocol 2001) document literature indicating fecal coliform contribution to bodies of water from bird populations. USEPA Protocol Developing Pathogen TMDLs (2001) documents that waterfowl such as geese, ducks, and heron can contaminate surface water with microbial pathogens. However, no specific study has been conducted to investigate fecal coliform contributions from birds in Galveston Bay to date. Fecal coliform contributions from birds is discussed in detail in Section 5.3 of this report. Estimation of fecal coliform loadings to study area from laughing gull species is also presented.

2.2.5 Sediment

Re-suspension of sediment is mentioned as source of bacteria as general literature based on the fact that sediment often shows higher concentration of bacteria than in the water overlying it. Rafai and Jensen report (2001) states that sediments have been shown to contain fecal coliforms at higher concentrations compared to overlaying water column after reviewing extensive literature. A review of general literature indicated that sediments present appropriate condition for an extended survival of bacteria (Rafai and Jensen 2001, Crabill et al 1998). Study performed in marine waters in Sydney, Australia (Daves et al. 1995) suggests sediments provide a favorable, nonstarvation environment for the bacteria. However, growth of fecal coliform in sediments is not confirmed in published literature.

2.4 Classification of Molluscan Shellfish Growing Areas

Proper classification of molluscan shellfish growing areas is necessary to protect the oyster-consuming public from illness associated with shellfish grown in and harvested from waters in the state of Texas. Classification is determined based on available information including sources of non-point and point source pollutants, bacteriological quality of bay water and other environmental and physical factors which alone or, collectively, detrimentally affect water quality (TDH 2000).

The seafood safety division (SSD) of the Texas Department of Health (TDH) is responsible for maintaining proper classification of molluscun shellfish growing waters for the State of Texas under the authority of Chapter 436, Health and Safety Code. Texas Department of Health conducts shoreline surveys to document point and non-point sources of pollution, bacterial sampling of bay water and documents the molluscan shellfish growing waters of the Galveston Bay system in Sanitary Survey reports (TDH 2000).

The shellfish growing area is classified into four different classes: *approved, conditionally approved, prohibited* and *restricted*. Shellfish markers are placed in the estuary to mark the boundary points of different classified segments.

The *approved* areas are generally open for oyster harvesting; *conditionally approved* areas are open to harvest of oysters from private leases under special permits from Texas Parks and Wildlife Department (TPWD). The areas open to the harvesting of shellfish are subject to closure by the seafood safety division (SSD) of the Texas Department of Health (TDH) due to heavy rainfall, high river stage, unacceptable bacteriological results, discharge of toxic materials, presence of biotoxins, or two or more confirmed illnesses linked to the impaired segment (TDH 2001).

Prohibited areas are the buffer zones which are closed due to proximity to the land surface irrespective of their fecal coliform concentration. The *restricted* areas are closed for oyster harvesting for not meeting the state's water quality criteria.

A 1995 Shellfish Classification Map developed by National Atmospheric and Oceanic Administration (NOAA) together with the 2001 shellfish markers is displayed in Figure 2.4.1. The 2002 shellfish classification map shown in Figure 2.4.2 is developed from the paper map provided by Texas Department of Health.

Comparison of the 2002 map with the 1995 map shows a significant increase in the *conditionally approved* area, a decrease in the *approved* area and a slight decrease in the *restricted* area for the impaired segments.

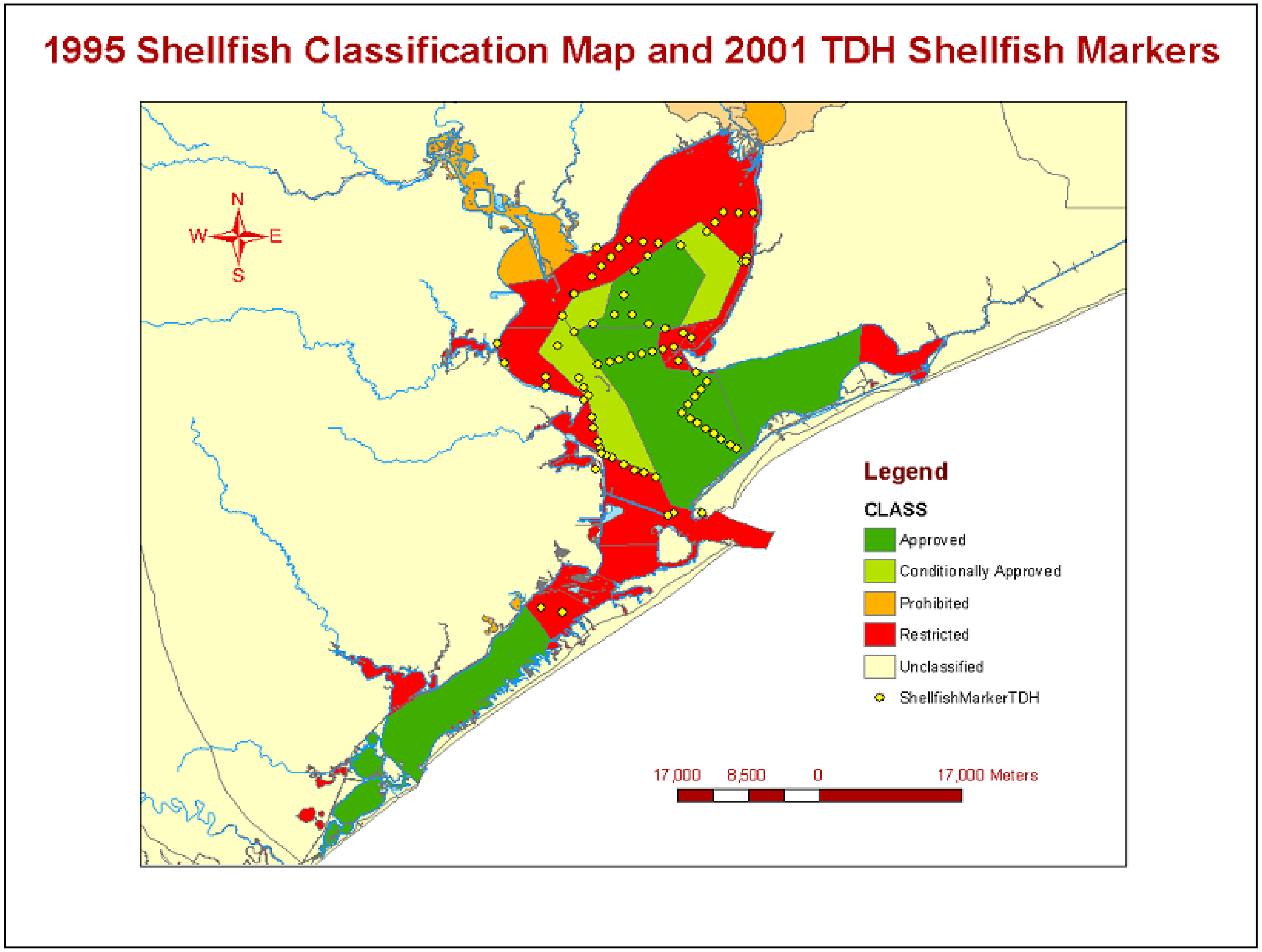


Figure 2.4.1: 1995 Shellfish Classification Map

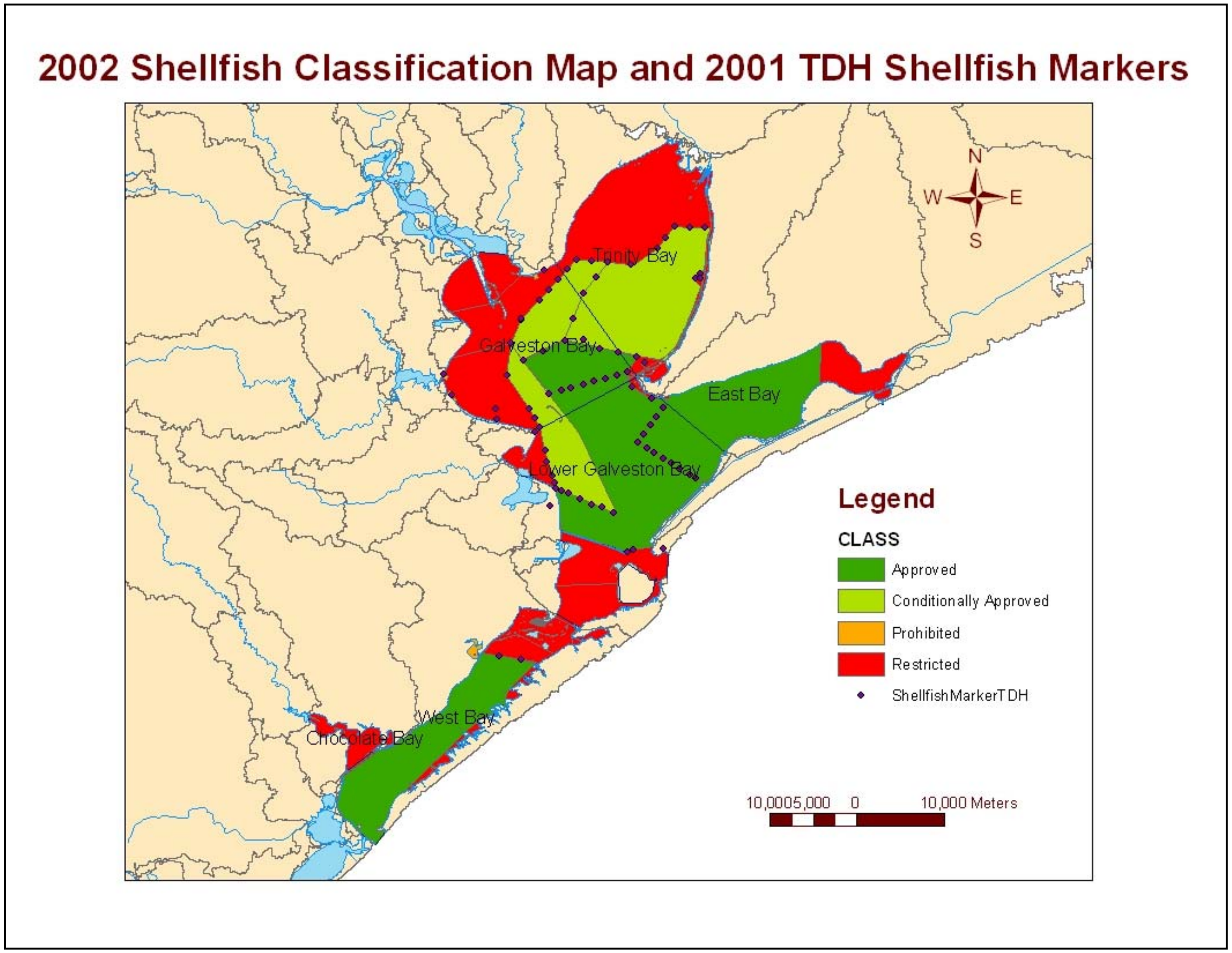


Figure 2.4.2: 2002 Shellfish Classification Map

CHAPTER 3: DATA DESCRIPTION

3.1 Bacterial Monitoring Data

3.1.1 INTRODUCTION

Bacterial monitoring dataset for the impaired segments and the study area watershed was acquired with an intention to analyze them in order to examine and assess the occurrences of elevated fecal coliform concentration. Monitoring dataset is also required to verify the expected concentration from Continuous Stirred Tank Reactor (CSTR) modeling using estimated loadings. Comparison of modeled value of fecal coliform concentration with observed values is important to identify level of uncertainty.

Monitoring dataset for the time period of January 1995 to December 2001 is acquired from Texas Department of Health (TDH) and Texas Commission on Environmental Quality (TCEQ) database for Galveston Bay Oyster Water Project.

3.1.2 TEXAS DEPARTMENT OF HEALTH MONITORING DATA

Fecal coliform concentration dataset 103 TDH monitoring stations located in the impaired segments is compiled under this study. The dataset is comprised of 10,323 data values during the six year time period. These datasets are sampled using MPN sampling method. The MPN sampling method is described in details in chapter 2 of this report. The concentration values obtained using this method ranges from 2 to 1600 MPN, which is the detectable range for this method.

TDH administers water quality sampling to obtain these data. Sampling is conducted under adverse conditions as defined by the National Shellfish Sanitation program (NSSP) Model Ordinance, 1997 Revision. Water samples are collected from a depth of two feet (TDH 2000).

3.1.2 TEXAS COMMISSION ON ENVIRONMENTAL QUALITY MONITORING DATA

Water quality monitoring data are stored with different ‘storet codes’ in the TCEQ database, where each storet code describes a unique water quality parameter. A total of 95,084 data values were made available from TCEQ database describing different water quality parameter in the impaired segments and the study area watershed for the time period of January 1995 to December 2001. 21,787 of these data values are fecal coliform concentration data.

Fecal Coliform concentration data available under storet code 79835 and 31616 are used for analysis in this study. Descriptions of these two storet codes are presented in Table 3.1.1 (Source: TCEQ website).

Storet_id	Short desc 1	Short desc 2	Meas Unit	Long Description	Min Value	Max Value
79835	FEC COLI	MPN	# /100ML	FECAL COLIFORM MPN/100ML 5/2,3 DIL FERMENT METHOD	0.900	100000.000
31616	FEC COLI	MFM-FCBR	# /100ML	FECAL COLIFORM, MEMBR FILTER, M-FC BROTH, #/100ML	0.900	100000.000

Table 3.1.1: Description of TCEQ Fecal Coliform Concentration Data

Fecal coliform concentration data for 124 monitoring stations located in the impaired segments are available under storet code 79835. The dataset is comprised of 8,136 data values for the six year time period. These dataset are sampled using MPN method and consequently limited by a range of 2 to 1600 colony forming unit per deciliter though the storet description states the range to be 0.900 to 100000.000 cfu per deciliter.

Fecal coliform concentration data for 435 TCEQ monitoring stations are available under storet code 31616. Most of these monitoring stations are located in the watershed draining to the impaired segment and few in the impaired segments. The dataset is comprised of 13,653 data values for the six year time period. These dataset are sampled using Membrane Filtration Method which has larger detection range compared to MPN method. The storet description states the range to be 0.900 to 100000.000. However, the studied dataset has a minimum observed value of 1 and a maximum value 720,000.

3.2 Dataset Required for Loading Estimation

3.2.1 WATERSHED DELINEATION DATASET AND HYDROGRAPHY NETWORK

In order to compute non-point loadings to a waterbody it is required to identify the watershed or land-surface area that drains to the waterbody. A watershed can be defined as a drainage basin – the area of land from which water drains into a river, bayou, stream, lake or bay. Watershed delineation is accomplished by processing digital elevation models (DEM) using GIS to produce realistic watershed boundaries draining to specific waterbodies or stream segments.

Watersheds were delineated for the Texas Commisssion on Environmantal Quality (TCEQ) water quality management segments located in Basin Group B and C in two previous projects conducted at CRWR (Samuels & Maidment 2001 and Davis & Maidment 2000). Both these datasets are processed and used to develop the watershed delineation base-map for the Galveston Bay Oyster Water Project.

Samuels and Maidment (2001) studied water quality management segments in Basin Group C in Texas, composed of the Trinity-San Jacinto Coastal basin, the Trinity-San Jacinto Coastal Basin, the San Jacinto River Basin and the bays and estuaries associated with these basins. In this 2001 study, an algorithm was developed to water quality management segments, consisting of procedures to create a hydrography network, process digital elevation model and produce realistic watershed boundary. The data presented in this research is in Albers Equal Area Projection.

Watershed delineation dataset for the Basin Group B, Texas is available from Davis and Maidment (2000). Watersheds draining to Trinity River below Lake Livingston is taken from this study and included in the study area watershed. The dataset included the stream segment i.e. the Trinity River. Lake Livingston is created by creating a polygon from the stream boundaries.

Watershed delineation dataset obtained from Samuels and Maidment (2001) study is named *'watershed_galveston'* and the Davis and Maidment (2000) study is named *'watershed_trinity'* in association with their geographic location. The acquired watershed map is displayed in Figure 3.2.1.

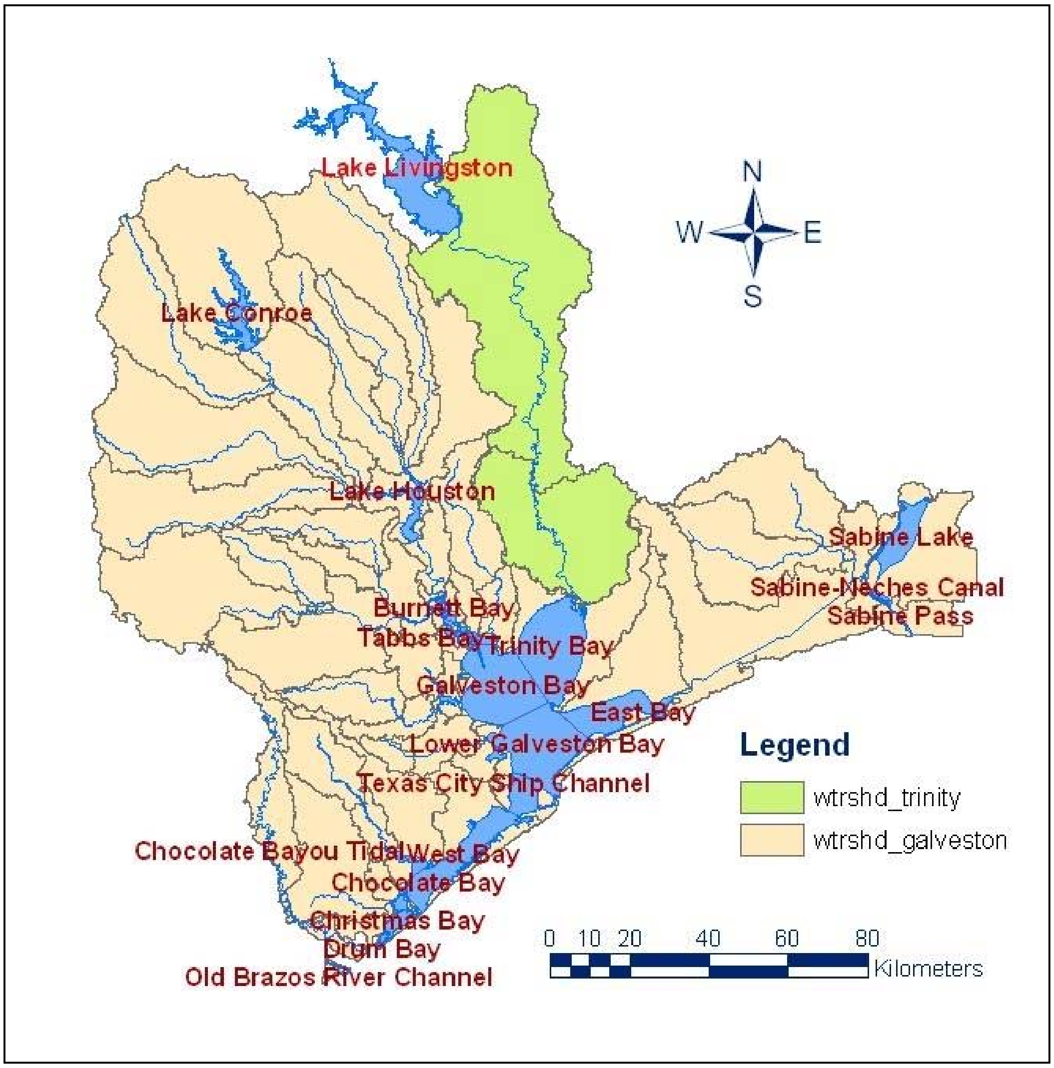


Figure 3.2.1: Watershed Delineation Map Acquired from Previous Study

The two watershed shape files 'watershed_galveston' and 'watershed_trinity' are imported to a geodatabase and projected with defined coordinate system (TSMS). The watersheds are then joined with the Geo-processing wizard. A few modifications are made to the combined watershed segment to produce the final watersheds used for computation of non-point loadings. A watershed segment located at the west side of the combined watershed drains directly to the Gulf of Mexico. This segment was deleted from the final watershed. Watershed segment located at the east side of Sabine Pass and containing Sabine Lake is also deleted because of the negligible flow to East bay arising from this segment.

The stream networks and water bodies acquired from the two former studies are joined in the same manner. The joined stream network is named '*HydroEdge*' and water bodies are named '*Waterbody*'. The final watershed delineation base-map used in the project including the stream network and waterbody is displayed in Figure 3.2.2. The abandoned segments are marked in circles in the figure.

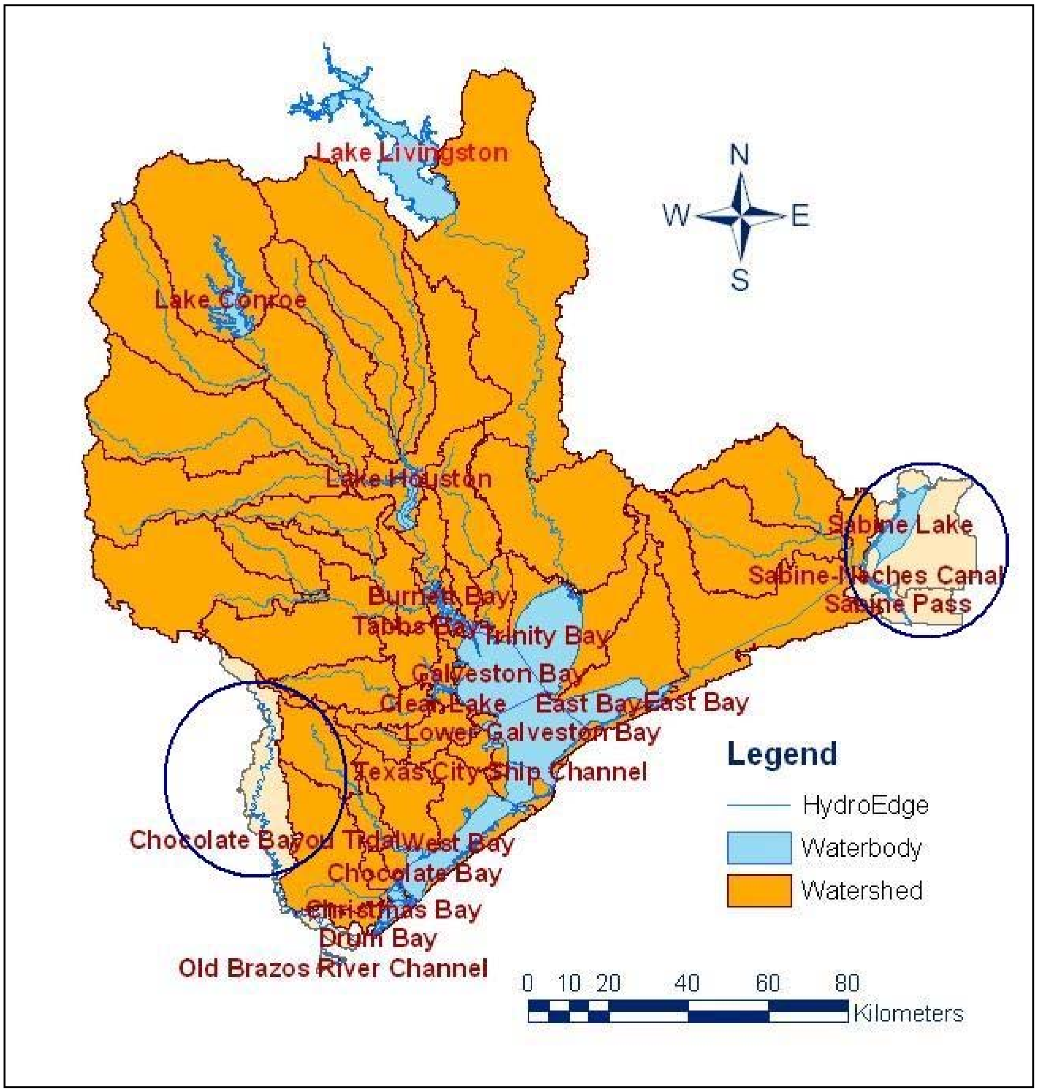


Figure 3.2.2: Final Watershed including Stream Network and Water bodies

The final watershed feature class including 51 watershed segments has an area of 8556 square miles (22160.26 square kilometers) including the lakes and estuaries located in the study area watersheds. Each of the watershed segment corresponds to a Texas Commission of Environmental Quality (TCEQ) water quality management segment.

3.2.2 Precipitation Data

A precipitation grid for the state of Texas was available from CRWR database. The source of the precipitation data is Oregon State University's Forest Science Department. The precipitation data from Oregon State University is a mean annual precipitation grid for the United States based on the years 1961 to 1990. The grid was developed using an interpolation process called PRISM (**P**arameter-elevation **R**egressions on **I**ndependent **S**lopes **M**odel), and is verified by consultation with State Climatologists (Quenzer & Maidment, 1998).

The grid contains mean annual rainfall data in mm per year. Spatial reference for the dataset is NAD_1983_Albers projected coordinate system and the geographic coordinate system is GCS_North_American_1983. The unit of precipitation is in inches per year.

3.2.3 Land-use / Land-cover Data

Concentration of contaminants varies with different land use and land cover types. A land use / land cover dataset is, therefore, required for non-point load estimation from the project watershed.

The United States Geological Survey (USGS) Land Use Land Cover (LULC) data with the scale of 1:250000 are available from USGS website http://edc.usgs.gov/geodata/. LULC dataset was downloaded for the quadrangles Houston, Texas and Beaumont, Texas for this study.

The Land Use and Land Cover (LULC) data files describe the vegetation, water, natural surface, and cultural features on the land surface. The United States Geological Survey (USGS) provides these data sets and associated maps as a part of its National Mapping Program.

The metadata of this data set states “This is land use / land cover digital data collected by USGS and converted to ARC/INFO by the EPA. This data is useful for environmental assessment of land use patterns with respect to water quality analysis, growth management, and other types of environmental impact assessment.”

The USGS land use data are meant to be used by quadrangle or among adjacent quadrangles where temporally contiguous and may be used in any geographic application where intermediate scale land use data are appropriate and the dates are representative. Each quadrangle of land use data has a different representative date. Date ranges from mid 1970s to early 1980s are common.

Manual interpretation of aerial photographs acquired from NASA high-altitude missions and other sources were first used to compile the land use land cover maps. Secondary sources from earlier land use maps and field surveys were also incorporated into the LULC maps as needed. At a later time, the LULC maps were digitized to create a national digital LULC database. The evolution of this process resulted in the creation of the Geographic Information Retrieval Analysis System (GIRAS) (Source: Condensed User Guide, USGS).

Initial source preparation involves the transfer of field survey information, photo classification detail and associated line work to a base map for digitization. Adjacent maps are also checked to ensure continuity. The maps are digitized and the appropriate classification codes are assigned for processing through GIRAS and checked for accuracy. All LULC data conform to the Universal Transverse Mercator (UTM) projection (Source: Condensed User Guide, USGS).

The USGS Land Use Land Cover Data uses the Anderson Land Use Code classification system, in which land use types are broken into 9 basic categories with the second digit distinguishing subcategories of the principal categories (Anderson et. al. 1976). The classification system is attached as Appendix A. Figure 3.2.3 shows USGS land use categories for the study area.

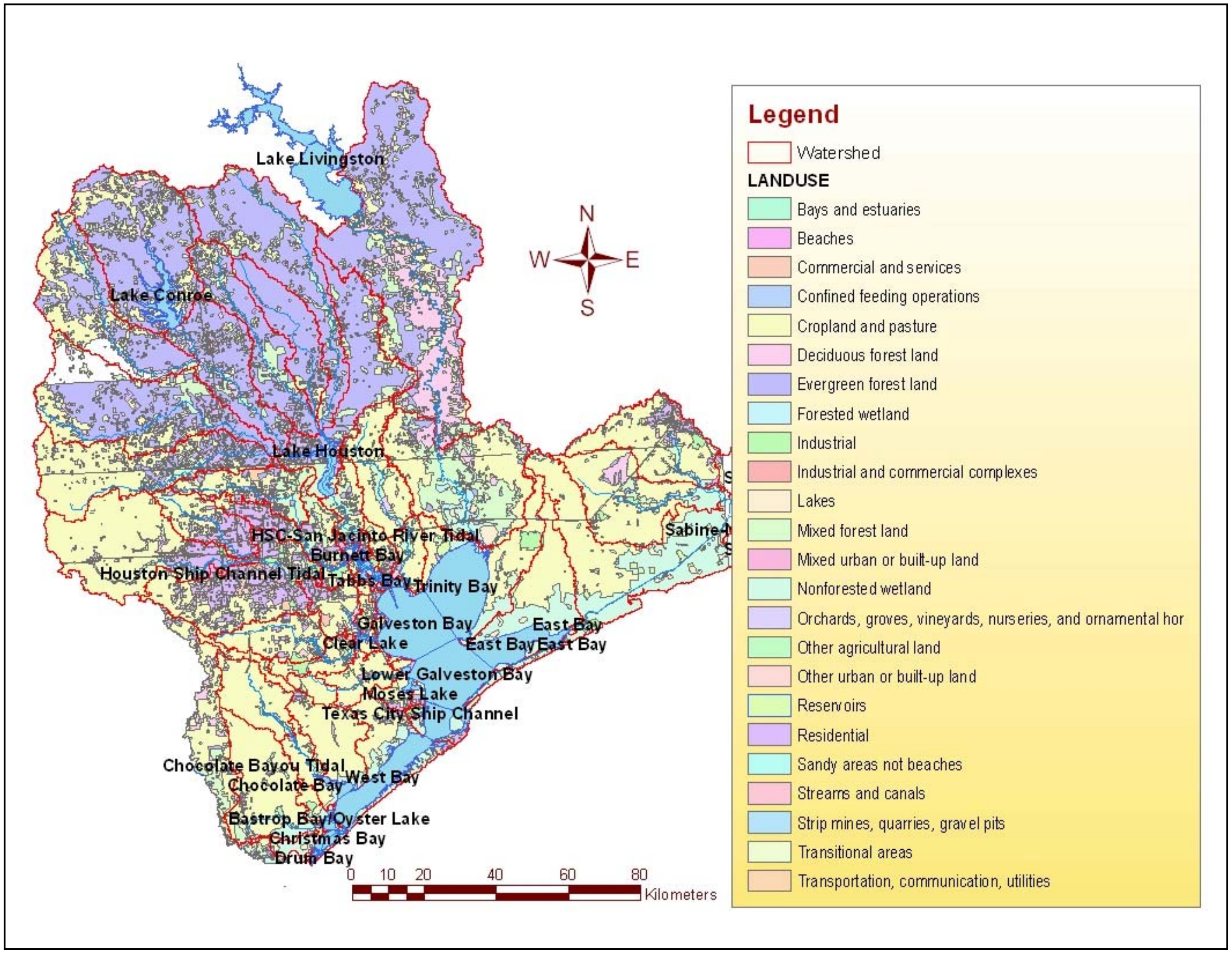


Figure 3.2.3: USGS Land use Categories in the Study Area Watershed

3.2.4 EVENT MEAN CONCENTRATION (EMC)

Event Mean Concentrations (EMC) are typical pollutant concentration values found in runoff water from particular land uses. Loads are calculated using the relationship: Load Mass = EMC × Runoff. In order to identify EMC values for fecal coliform bacteria for this project, values compiled by several previous studies were researched.

The Galveston Bay National Estuary Program Non-point Source Characterization (NPS) study undertaken by Newell et al (1992) has put together EMC values from various sources. The major sources for EMC data were the Rice University Non-point Source Characterization studies, the USGS Houston Runoff Program Data, and the Texas Water Commission / Winslow Associates Houston Ship Channel Non-point Source Characterization study. Other sources included data from EPA Nationwide Urban Runoff Program (NURP), the Priority Pollutant Survey from the NURP Program, the USGS Austin NPS study, and various agricultural NPS studies. Fecal EMC values for fecal coliform bacteria used by this study and relative accuracy of these values are tabulated in Table 3.2.1.

Land Use Category	FC EMCs (colonies/100ml)	Estimated Relative Accuracy
High Density Urban	22000	Good
Residential	22000	Good
Agricultural	2500	Fair
Open/Pasture	2500	Fair
Forest	1600	Good
Wetlands	1600	No Data
Water	0	No Data
Barren	1600	Fair

Table 3.2.1: Project EMC values used by GBNEP NPS study (Newell et al. 1992)

The 1996 Corpus Christi Bay National Estuary Program (CCBNEP) study (Baird & Ockerman 1996) compiled EMC values from the National Pollution Discharge Ellimination System (NPDES) study for Corpus Christi, Dallas-Fort Worth and San Antonio; the Galveston Bay National Estuary Program NPS study; and the nationwide Urban Runoff Program. Project EMC values used in this study that are relevant to Corpus Christi Bay area. However, these values were useful as reference for the current study when no other EMC data were available for specific land use categories. Table3.5.2 presents the summary of Fecal Coliform EMC values by land use categories for the CCBNEP study area.

Constituent	Land Use Category						
	Residential	Commercial	Industrial	Transportation	Cropland	Rangeland	Undeveloped /Open
Fecal Coliform (colonies/ 100 ml)	20,000	6,900	9,700	53,000	--	37	--

Table 3.2.2: Summary of Fecal Coliform EMC values for CBNEP study area (Baird and Ockerman 1996)

The final EMC database for fecal coliform bacteria for the Galveston bay study area is put together by incorporating EMC values in Galveston Bay area compiled by previous studies discussed above and best professional judgment (Personal Communication, Dr. George Ward, Ptofessor, University of Texas at Austin, December 2002) as presented in Chapter 5 of this report.

3.2.6 SALINITY

Information about the salinity is important to identify deactivation rates of bacteria in the study area. In addition to literature data available on salinity in the study area, datasets on salinity for the impaired segments are acquired from the TCEQ database for the time period of January 1985 to November 2002. Unit of salinity data value reported in the TCEQ database is in Practical Salinity Unit (psu) or parts per thousand. Data values represent an average value during a 24-hr period.

Salinity Statistical summary (i.e. minimum, maximum, mean, sum and count) for the salinity dataset (January 1985 to November 2002) is computed for the study area. Statistics of salinity data for each monitoring station in the Galveston Bay is presented in Appendix B. Summary of the salinity dataset is shown in Table 3.2.3.

Table 3.2.3: Statistical Summary of Salinity Data:

Seg ID	Segment Name	Number of Stations	Minimum (PSU)	Maximum (PSU)	Average (PSU)	Count of Data Values
2421	Upper Galveston Bay	56	0.0	29.8	12.4	6707
2422	Trinity Bay	4	0.0	31.3	6.8	334
2423	East Bay	17	0.0	28.2	11.5	2675
2424	West Bay	3	1.0	33.0	17.5	334
2432	Chocolate Bay	4	1.0	32.9	14.6	147
2439	Lower Galveston Bay	1	2.8	29.5	18.4	501

3.2.7 BATHYMETRY DATA

Bathymetry data or water depth is an important feature of aquatic systems which describes physical shape of the system and monitor changes in the shape caused by sedimentation. For this study, a bathymetry dataset was used for computing the volumes of water in the impaired segments.

Bathymetry data for the coast of Texas was downloaded in the form of point shape file from TNRIS website http://www.tnris.state.tx.us/DigitalData/data_cat.htm. The dataset originated from the National Oceanic and Atmospheric Administration and the Texas General Land Office. It contains bathymetry (depth soundings) in meters and feet for bays and the offshore zone of Texas. This bathymetry dataset was generated from latitude/longitude coordinates acquired from the National Oceanic and Atmospheric Administration (NOAA) Hazardous Materials and Response Division. Metadata about the dataset is available at the website. Bathymetry data points for the coast of Texas are shown in figure 3.2.4.

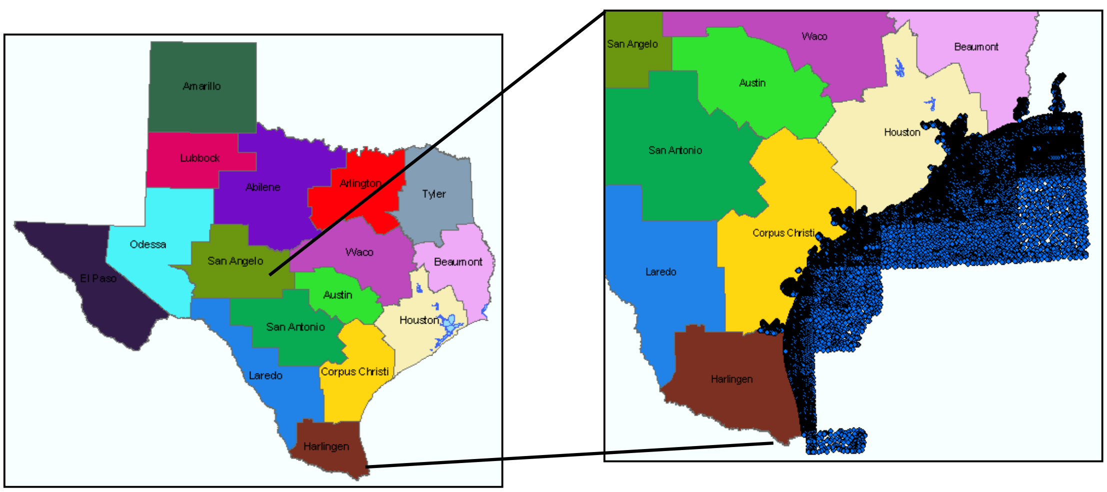


Figure 3.2.4: Bathymetry data for the coast of Texas from TNRIS website

Spatial reference information about the bathymetry data is stated below.

Spatial_Reference_Information:
Horizontal_Coordinate_System_Definition:
Geographic:
Latitude_Resolution: 0.000000
Longitude_Resolution: 0.000000
Geographic_Coordinate_Units: Decimal degrees

Geodetic_Model:
Horizontal_Datum_Name: North American Datum of 1927
Ellipsoid_Name: Clarke 1866
Semi-major_Axis: 6378206.400000
Denominator_of_Flattening_Ratio: 294.97869

The bathymetry shape file of Texas is clipped to create a bathymetry shape file for the six impaired segments of Galveston Bay. The coordinate system of the shape file is defined and converted to TSMS. The dataset is displayed in Figure 3.2.5.

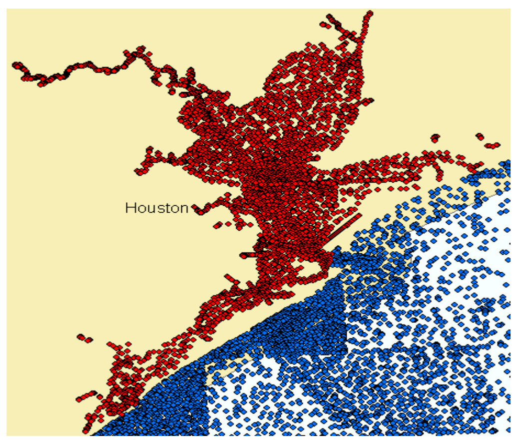


Figure 3.2.5: Bathymetry data for project area in Galveston Bay

A 30 m X 30 m bathymetry grid is created by interpolating the shape file to raster using inverse distance weighted method using the Spatial Analyst in ArcMap. The field Z_value was used for creating the grid, which is the depth of bay in meter. The mean depth of each bay segment is calculated using the Zonal Statistics under Spatial Analyst.

3.2.8 USGS STREAM GAUGE DATA

USGS stream Gauge data was used to compare the estimated runoff flow from the watersheds. Mean annual flow data for all stations located in study area watershed is downloaded from USGS website. Location of the USGS gauging stations are stored as feature class *MonitoringStation* in the ArcHydro geodatadase. Mean annual stream flow at each gauging station is computed using the available data.

3.3 Map Projection and Coordinate Systems

3.3.1 INTRODUCTION

The different datasets used in this project were retrieved from different sources and research projects. Consequently, they were obtained in different map projection and coordinate systems. It is important to define all the datasets with a specific co-ordinate system for consistency and accuracy while performing GIS processing and computation involving multiple data layers.

The Texas State Mapping System (TSMS) is the chosen map projection system for this project in compliance with Texas Commission on Environmental Quality (TCEQ)'s requirement for data delivery. TSMS is the preferred mapping system used by most state agencies in the state of Texas including Texas Commission on Environmental Quality (TCEQ) at present.

3.3.1.1 Texas State Mapping System

The Department of Information Resources (DIR) and the Texas Information Council (TGIC) adopted a standard statewide coordinate system for all digital data relating to Texas in 1992 (Shackelford, 2000). The coordinate system parameters were designed to portray a statewide coverage of Texas without any gap and with a pleasing shape. Texas State Mapping System is a

Lambert Conformal Conic Projection in which standard parallels are located at 1/6 from the top and bottom of the state (Samuels and Maidment 2001). The parameters for TSMS are presented in Table 3.3.1.

Table 3.3.1: Parameters for Texas State Mapping System (TSMS)

Texas State Mapping System (TSMS)	
Projection	Lambert Conformal Conic
Spheroid	Clarke GRS 80
Datum	North American Datum of 1983 (NAD83)
Longitude of Origin	100 degrees West (-100)
Latitude of Origin	31 degrees 10 minutes North (31.16)
Standard Parallel #1	27 degrees 25 minutes North (27.416)
Standard Parallel #2	34 degrees 55 minutes North (34.916)
False Easting	1,000,000 meters
False Northing	1,000,000 meters
Units of Measure	meters

CHAPTER 4: ANALYSIS OF MONITORING DATASET

4.1 Spatial Distribution of Fecal Coliform

4.1.1 METHODOLOGY

Analysis of bacterial monitoring dataset in the impaired segments and study area watershed is performed using fecal coliform since available observed data in the Galveston Bay segments are in fecal coliform counts. Use of fecal coliform for analysis is also convenient as the water quality criteria for oyster water use applicable to this study are set in terms of fecal coliform counts.

The monitoring dataset for fecal coliform for the time period of January 1995 to December 2001 acquired by Texas Department of Health and TCEQ are analyzed to determine any spatial pattern in the occurrences of elevated fecal coliform concentration. Statistical parameters of observed dataset at each monitoring stations are computed and mapped using graduated symbols in ArcMap in order to illustrate relative magnitude of fecal coliform concentration at different location.

4.1.2 PROCEDURE OF APPLICATION

Minimum, maximum, geometric mean, arithmetic mean, median, and count of fecal coliform concentration at each monitoring station located in the impaired segments are computed. Arithmetic mean, minimum, maximum and count values for each station is computed utilizing querying capabilities of Microsoft Access. The queries were grouped by station number to obtain statistical parameter for each station. Statistical parameters bacterial monitoring data obtained for each monitoring stations located in Galveston Bay in presented in Appendix C and for monitoring stations located in study area watershed is presented in Appendix D.

However, neither Excel nor Access is capable of computing median and geometric mean values grouped by station for large dataset as this one. Visual Basis scripts are written for Microsoft Excel to compute median and geometric mean values grouped by station number for TCEQ and station ID for TDH dataset. These visual basic scripts are attached as Appendix E. Dbf files are created with the statistical parameters for each station.

The geometric mean of a sequence $\{a_i\}_{i=1}^{n}$ is defined by

$$G(a_1, \ldots, a_n) \equiv \left(\prod_{i=1}^{n} a_i \right)^{1/n}. \qquad (4.1.1)$$

Thus,

$$G(a_1, a_2) = \sqrt{a_1 a_2} \qquad (4.1.2)$$

$$G(a_1, a_2, a_3) = (a_1 a_2 a_3)^{1/3}, \qquad (4.1.3)$$

and so on.

TDH and TCEQ monitoring stations are mapped using ArcMap from their latitude and longitudes. Once the stations are mapped, they are joined with the data files using station number for TCEQ stations and station ID for TDH stations. Several maps are created using graduated symbols and different statistical parameters at the monitoring stations which are presented in the Chapter 6 of this report.

4.1.3 RESULT

4.1.3.1 Spatial Distribution of Fecal Coliform in the Impaired Segments

A map of mean values TDH and TCEQ fecal coliform concentration data at each monitoring station in the impaired segments is presented in Figure 4.1.1. It is important to note that the source of much of the TCEQ dataset located in the impaired segment is TDH monitoring data. Consequently, the observed data from the regulatory agency are very similar. Figure 4.1.2 and 4.1.3 presents the median and geometric mean values of the monitoring dataset. Geometric mean values dampen the effect of the high values and resemble the median values more closely.

Mapping of fecal coliform concentration in impaired segments shows the ‘Hot Spots’ of high fecal coliform concentration. High concentration zones are located where the Houston Ship Channel enters the Upper Galveston Bay and along the west shore of Galveston bay where the densely populated cities are located. A notable point is elevated level of fecal concentration can be observed along Houston Ship Channel which indicates loadings from boat traffic.

4.1.3.2 Spatial Distribution of Fecal Coliform in Study Area Watershed

Three maps are created with relative spatial distributions of fecal coliform concentration in study area watershed. Figure 6.1.4 shows arithmetic mean of fecal coliform count at different monitoring stations in study area watershed. The observed dataset show much higher fecal coliform concentrations in the streams located in study area watershed compared to the concentration in the bay revealing the fact that deactivation due to sunlight and salinity plays key role in the inactivation of bacteria.

Figure 6.1.5 presents a map mean fecal coliform concentration in the monitoring stations around Houston area. This map shows that the high concentration zone. Significantly higher fecal coliform counts are observed in the highly urbanized Houston area. Figure 6.1.6 presents maps of geometric mean values of fecal coliform concentration in the monitoring stations located at the study area watershed.

4.1.3.3 Summary of TDH and TCEQ Monitoring Dataset in the Impaired Segments

As discussed in earlier in this chapter, the source of most TCEQ data in the impaired segment is TDH. Consequently, statistical parameters for the two dataset are quite consistent. TDH data is used as the basis of comparison with the modeled expected concentration is this study. However, summary of TCEQ data is useful in to identify separate parameters for upper and lower Galveston Bay. Summary of TDH and TCEQ monitoring dataset are presented in Tables 4.1.1 and 4.1.2 respectively.

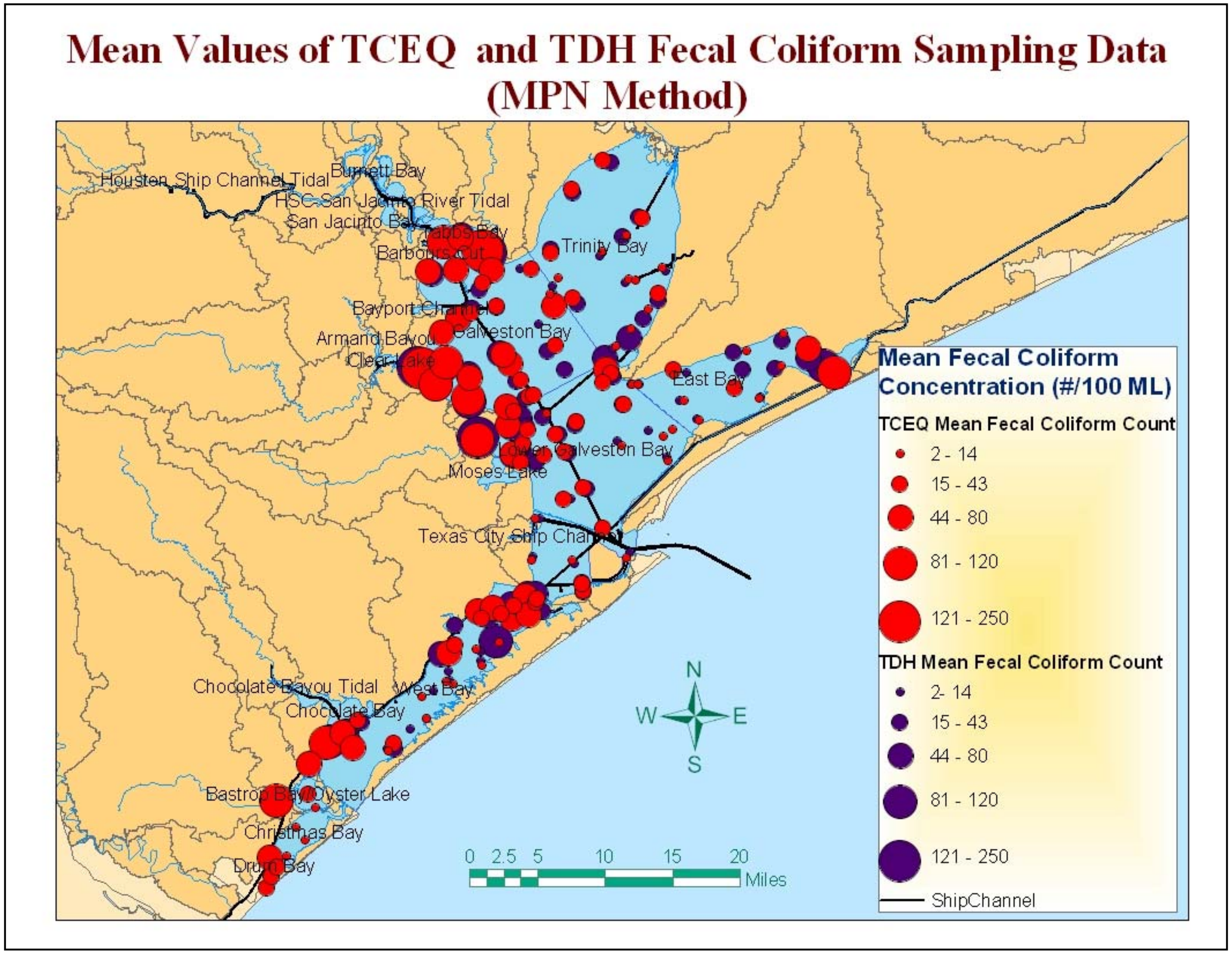


Figure 4.1.1: Arithmetic Mean values of Fecal Coliform Sampling Data at Galveston Bay Monitoring Points

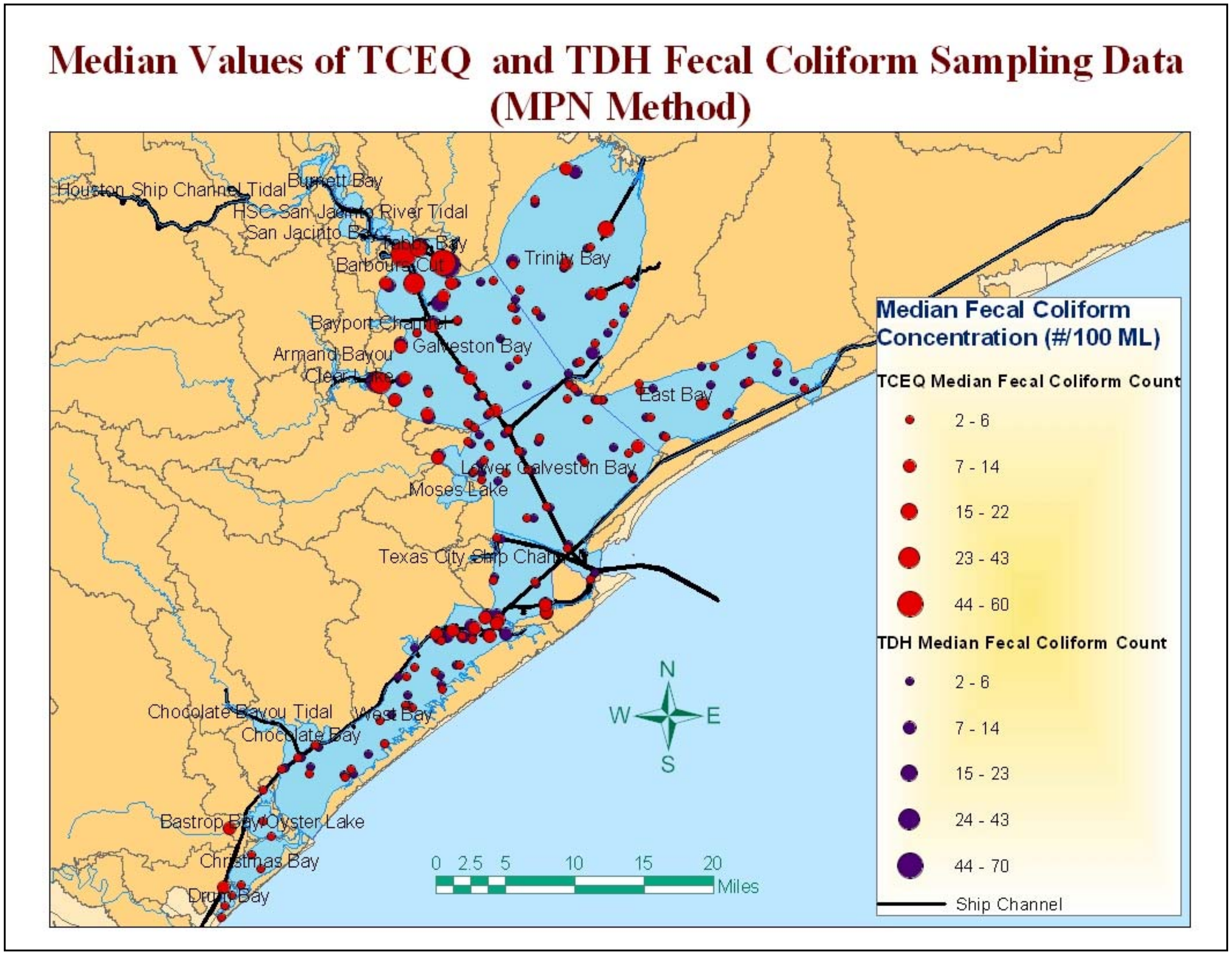


Figure 4.1.2: Median Values of Fecal Coliform Sampling Data at Galveston Bay Monitoring Points

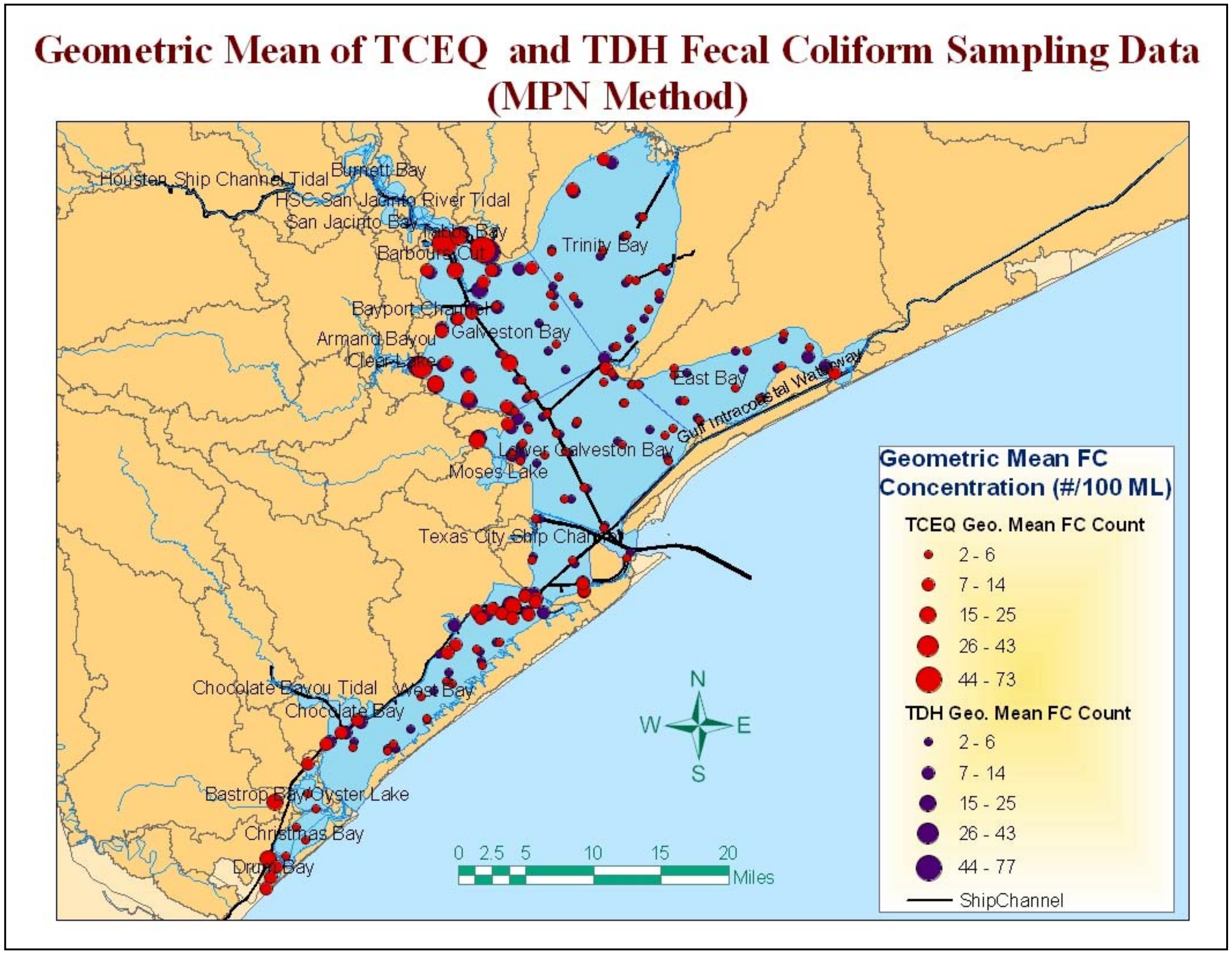


Figure 4.1.3: Geometric Mean Values of Fecal Coliform Sampling Data at Galveston Bay Monitoring Points

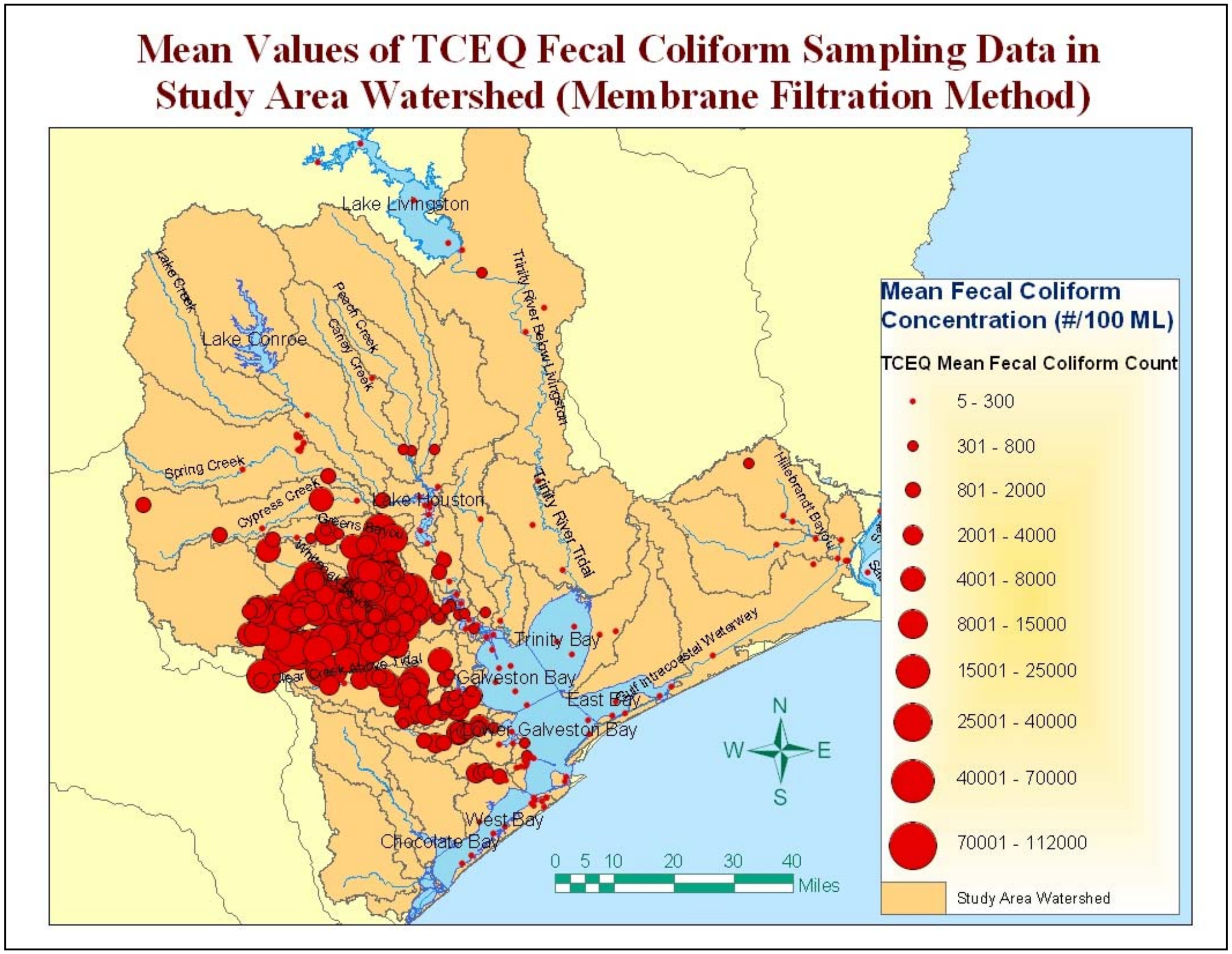


Figure 4.1.4: Arithmetic Mean Values of TCEQ Fecal Coliform Sampling Data in Study Area Watershed

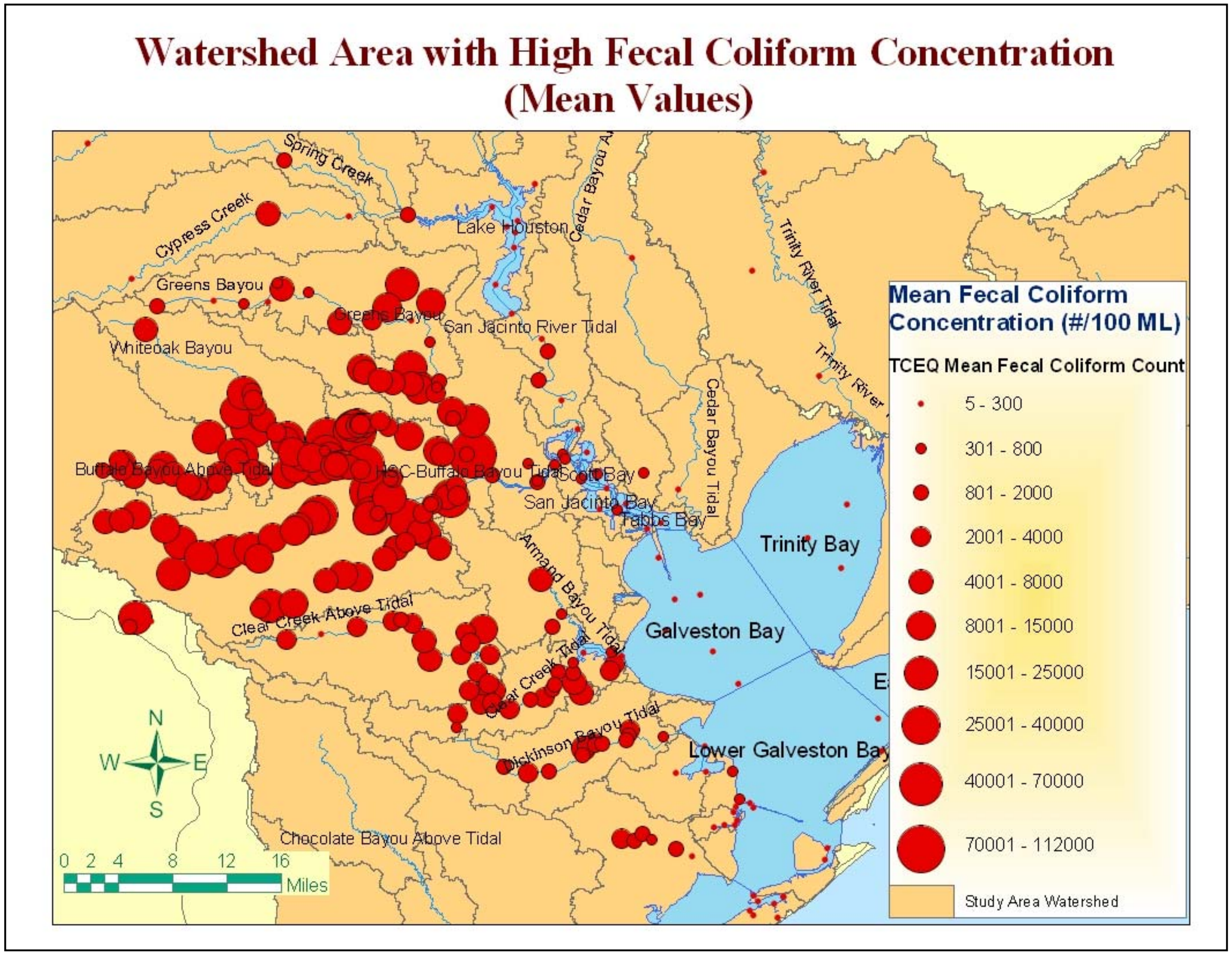


Figure 4.1.5: Close-up Map of Study Area Watershed with High Fecal Coliform Counts

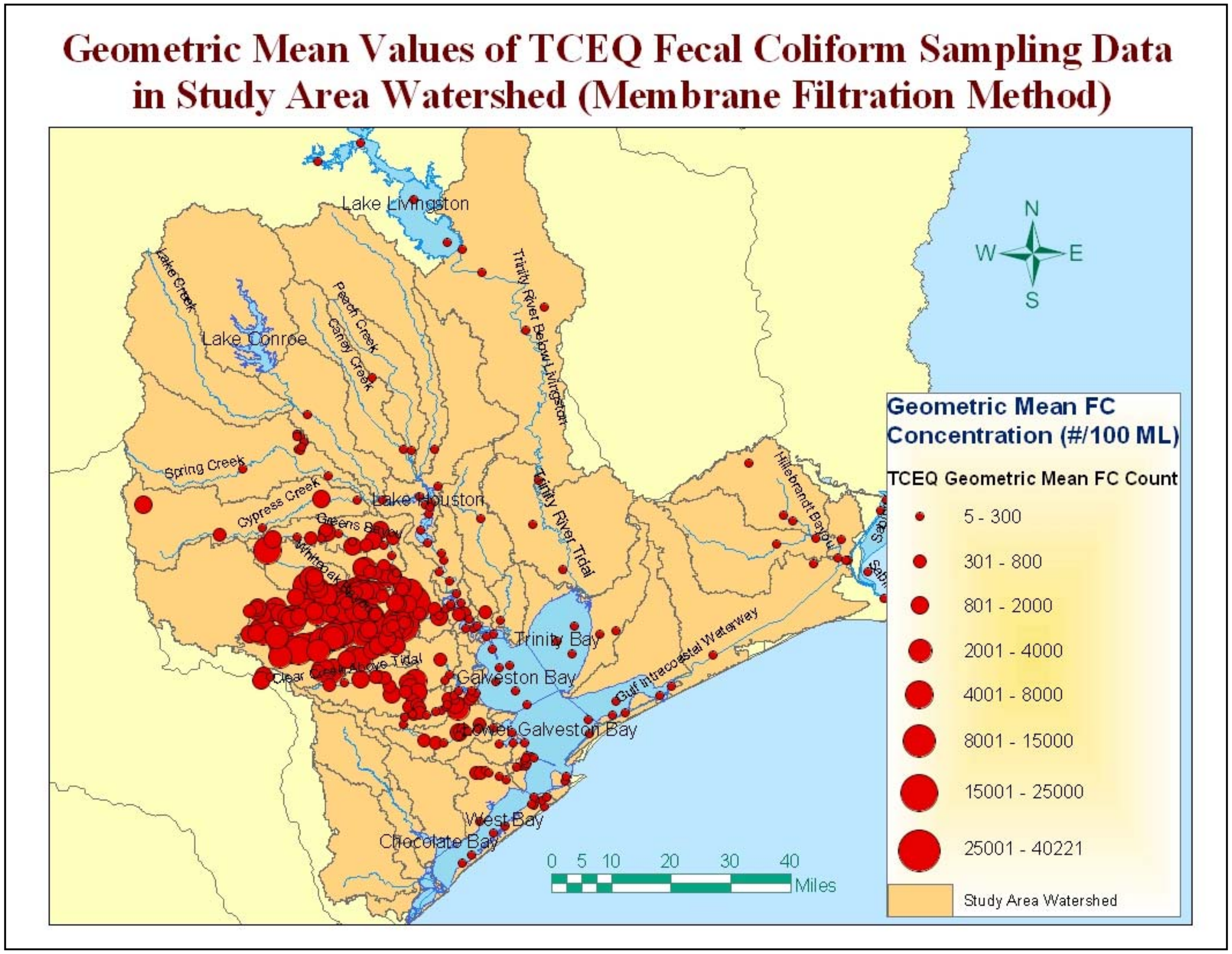


Figure 4.1.6: Geometric Mean Values of TCEQ Fecal Coliform Sampling Data in Study Area Watershed

Table 4.1.1: Summary of TDH Fecal Coliform Monitoring Data for the Impaired Segments

Segment ID	Segment Name	Number of Stations	Arithmetic Mean	Geometric Mean	Minimum	Maximum	Count of Data Values
2421	Upper Galveston Bay	--	--		--	--	--
2422	Trinity Bay	18	19.8	5.0	2	1600	1231
2423	East Bay	17	18.7	3.8	2	1600	1878
2424	West Bay	26	31.4	5.8	2	1600	1364
2432	Chocolate Bay	--	--		--	--	--
2439	Lower Galveston Bay	--	--		--	--	--
2421, 2439	Upper and Lower Galveston Bay	44	50.7	7.0	2	1600	5624

Table 4.1.2: Summary of TCEQ Fecal Coliform Monitoring Data for the Impaired Segments

Segment ID	Segment Name	Number of Stations	Arithmetic Mean	Geometric Mean	Minimum	Maximum	Count of Data Values
2421	Upper Galveston Bay	22	67.4	9.8	2	1600	2071
2422	Trinity Bay	19	22.2	5.1	2	1600	959
2423	East Bay	14	16.4	3.7	2	1600	1147
2424	West Bay	25	33.8	5.9	2	1600	939
2432	Chocolate Bay	--	--	--	--	--	--
2439	Lower Galveston Bay	28	30.4	4.8	2	1600	2431
2421, 2439	Upper and Lower Galveston Bay	50	47.4	6.6	2	1600	4502

4.2 Profiles of Fecal Coliform Concentration along Channels

4.2.1 METHODOLOGY

Spatial analysis of the observed data shows that the fecal coliform concentration in the streams and channels located in the upstream watersheds, within the Houston area, are much higher than the corresponding concentrations in Galveston Bay. In order to observe the change in concentration of fecal coliform along the streams and to examine changes near the estuary, profiles of mean fecal coliform concentration along three major stream channels running through the City of Houston namely Buffalo Bayou, Whiteoak Bayou and Greens Bayou are created.

Mean fecal coliform concentration at each station along the streams is plotted against the distance of the monitoring station from the mouth of the bay. The datasets presented in the profiles are TCEQ monitoring dataset that are sampled using Membrane Filtration method.

4.2.2 PROCEDURE OF APPLICATION

ArcHydro is a geospatial and temporal data model for water resources that operates within ArcGIS. The data model was used to create a Junction in relation to each monitoring station and place it on the network of channels and streams. An ArcHydro tool then calculated the distance of each station from the estuary using the built-in relationship of the junction and stream network.

ArcHydro geodatabase and tools are used to determine the distance of each TCEQ monitoring stations from the mouth of estuary. ArcHydro creates a Junction in relation to each monitoring station and places it on the network of channels and streams. An ArcHydro tool can then calculate the distance of each station from estuary using the built-in relationship of the junction and stream network once the geometric network is built and flow direction is set correctly.

Once the distance from each station along the channel is determined, mean fecal coliform concentration observed at the stations are plotted against distance. A map of the stream channel is included in each map for reference. The profiles along Greens Bayou, Whiteoak Bayou, and Buffalo Bayou are presented in Figures 4.2.1, 4.2.2 and 4.2.3 respectively.

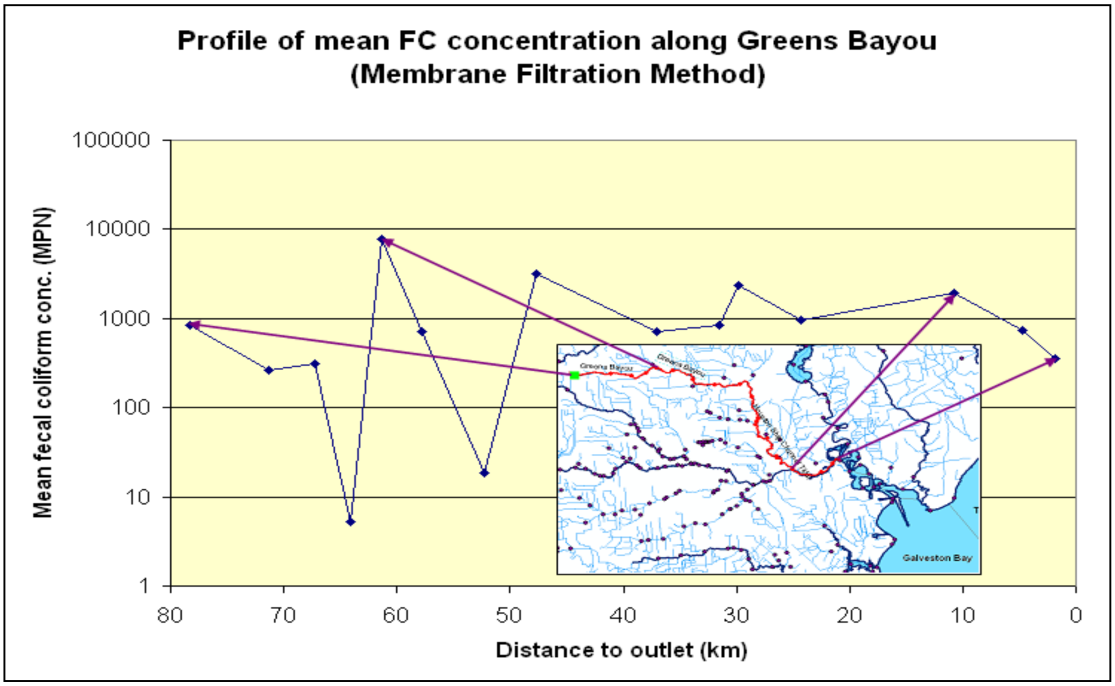


Figure 4.2.1: Profile of mean FC concentration (#/100ml) along Greens Bayou.

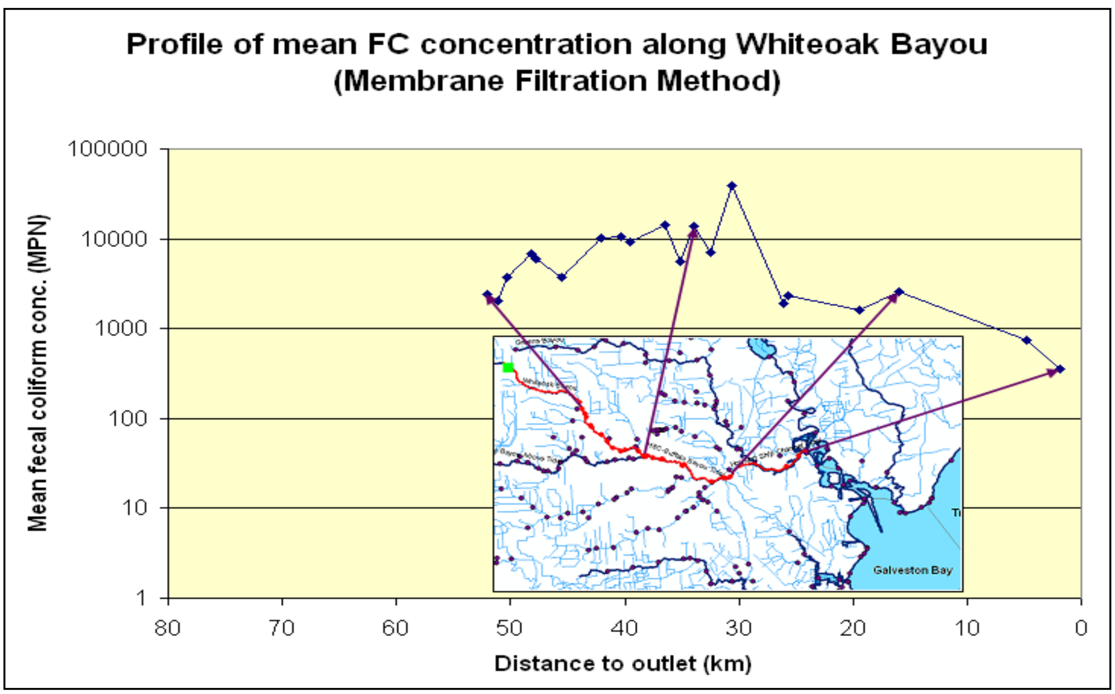


Figure 4.2.2: Profile of mean FC concentration (#/100ml) along Whiteoak Bayou.

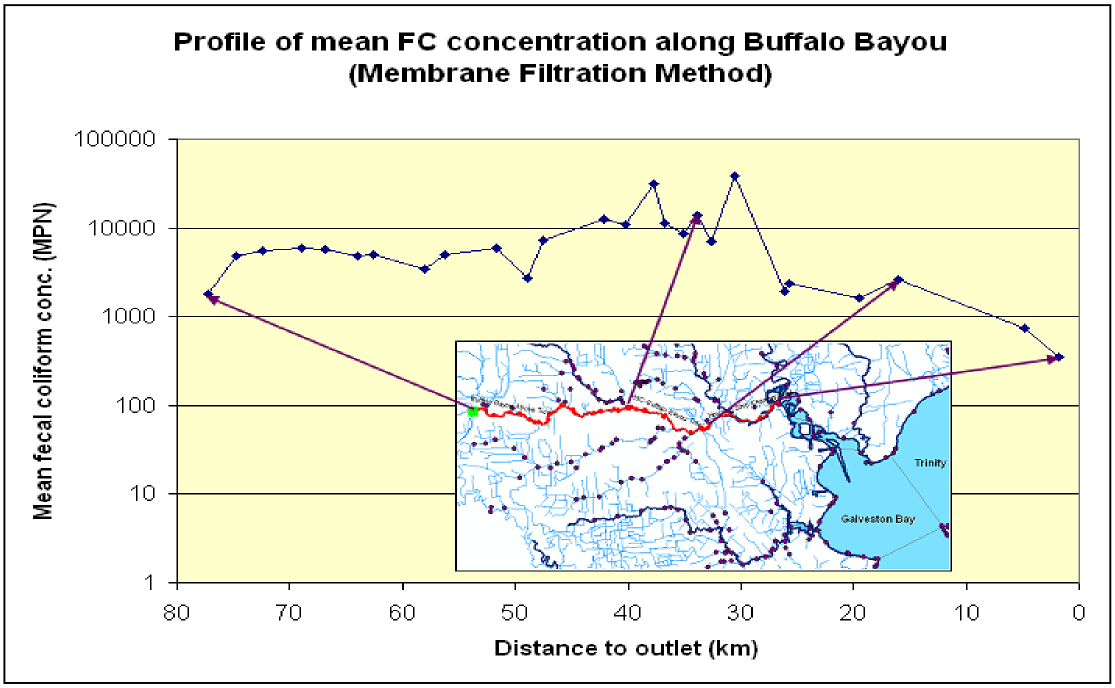


Figure 4.2.3: Profile of mean FC concentration (#/100ml) along Buffalo Bayou.

4.2.3 Result

The peaks in bacterial concentration observed in the monitoring dataset for Galveston Bay are random and could be caused by various factors including storm runoff, high winds, rainfall, tidal circulation etc. Profiles along stream channels in the Houston area, which is the high concentration zone of study area watershed, show spikes of high concentrations along the rivers and streams. Significant changes in fecal coliform concentration can be observed over short distances. These observations conform to proximity of cause-effect relationship of elevated fecal coliform concentrations and the fact that decay of bacteria plays a key role in controlling fecal coliform concentration in the bay.

4.3 Statistical Distribution of Fecal Coliform

4.3.1 METHODOLOGY:

Water quality standards for the impaired segments for water use are defined in terms of median values and upper 10% of observed concentration. Statistical consistency in observed fecal coliform dataset implies that the variable 'mean' is consistently related to the median and upper 10% values for the datasets and, therefore, justifies the use of mean values for loading estimation and modeling effort.

Frequency analysis of the observed dataset is performed using frequency factor. For the analysis, TDH monitoring dataset of fecal coliform concentration for East Bay, West Bay, Galveston Bay (Upper and Lower) and Trinity Bay are plotted on log scale against standard normal variable z. Data for all stations in each bay segment are combined to from the plot. The two criteria for oyster water use are marked in the graph as orange and red dots.

4.3.2 PROCEDURE OF APPLICATION:

4.3.2.1 Frequency Analysis using Frequency Factor

The frequency factor is applicable to many probability distribution used in hydrologic frequency analysis. For a normal or lognormal distribution the frequency factor is same as the standard normal variable z. The value of z corresponding to an exceedence probability of p (p = 1/T where T is return period) can be calculated by finding the value of an intermediate variable w

$$w = \left[\ln \frac{1}{p^2} \right]^{1/2} \quad (0 < p \leq 0.5) \tag{4.1}$$

Then calculating z using the approximation

$$z = w - \frac{2.515517 + 0.802853w + 0.010328w^2}{1 + 1.432788w + 0.189269w^2 + 0.001308w^3} \tag{4.2}$$

When p > 0.5, p is substituted with (1- p) in equation 4.1 and the of z computed by equation 4.2 is given a negative sign. The error in this formula is less than 0.00045 in z (Chow, Maidment & Mays 1988).

Plotting position refers to the probability value assigned to each piece of data to be plotted. If n is the total number of values to be plotted and m is the rank of a value in a list ordered by descending magnitude, the exceedence probability of the mth largest value, x_m, $P(X \geq x_m)$, is obtained by a plotting position formula, for a large n. Most plotting position formulas are represented by the following form:

$$P(X \geq x_m) = \frac{m - b}{n + 1 - 2b} \tag{4.3}$$

where b is a parameter. It is found that for a normally distributed data, Blom plotting position ($b = 3/8$) is closest to being unbiased (Chow, Maidment & Mays 1988).

4.3.2.2 Frequency Analysis for Observed Dataset

Frequency factors for the TDH monitoring dataset for the different bay segments are computed separately. First the data for each bay segment are ranked from largest ($m = 1$) to smallest ($m = n$) where n is number of data values.

Blom's plotting formula is used, since the data values in log scale are being fitted to normal distribution. The exceedance probability is calculated as $(m - 3/8)/(n + 1/4)$ using Blom's plotting formula. The corresponding value of the standard normal variable z in computed using equations 5.1 and 5.2. Once z is computed observed fecal coliform concentration are plotted in log scale against standard normal variable z for each bay segment. Observed fecal coliform concentration in East Bay is plotted against standard normal variable z in Figure 4.3.1.

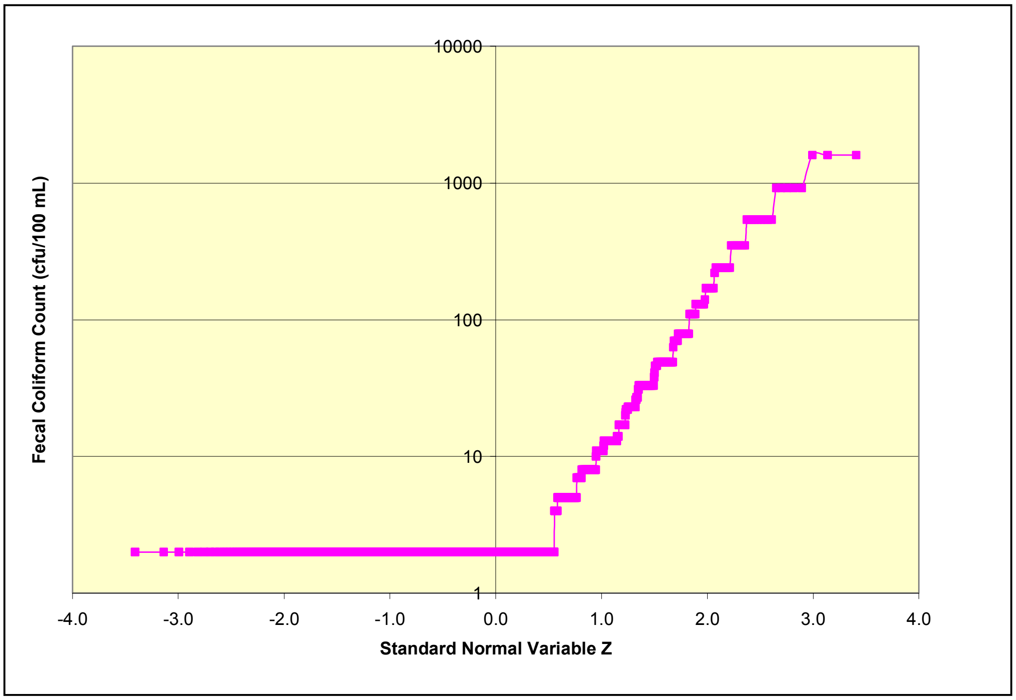


Figure 4.3.1: Distribution of fecal coliform concentration in East Bay

Observed fecal coliform dataset for all the bay segments are grouped together and presented in Figure 4.3.2. The two water quality criteria for oyster water use are marked in Figure 4.3.2. The orange dot shows the median coliform concentration of 14 MPN at z = 0. If the observed data at z = 0 is above 14 MPN or the orange dot, the bay segment is out of compliance for the first water quality criterion.

At z = 1.29, lower 90% of the observed data are located on the left of this point and the higher 10% are located on the right. The red dot is marked at z = 1.29 and fecal coliform concentration of 43 MPN. If the observed data at z = 1.29

is above 43 MPN or the red dot, the bay segment is out of compliance for the second water quality criterion.

TDH uses MPN method for the determination of fecal coliform concentration. The concentration values obtained using this method ranges from 2 to 1600 cfu/100ml, which is the detectable range for this method. Figure 4.3.2 shows a large number of observed values at the lower detection limit for all the bay segments; indicating ‘no detection’ at the lower end of the dataset.

Log values of observed dataset in the detectable range of MPN method are plotted in Figure 4.3.3 for all bay segments. Linear regression lines through log values of observed concentrations show log normal distribution in the detectable range of TDH monitoring dataset for fecal coliform in the impaired segments.

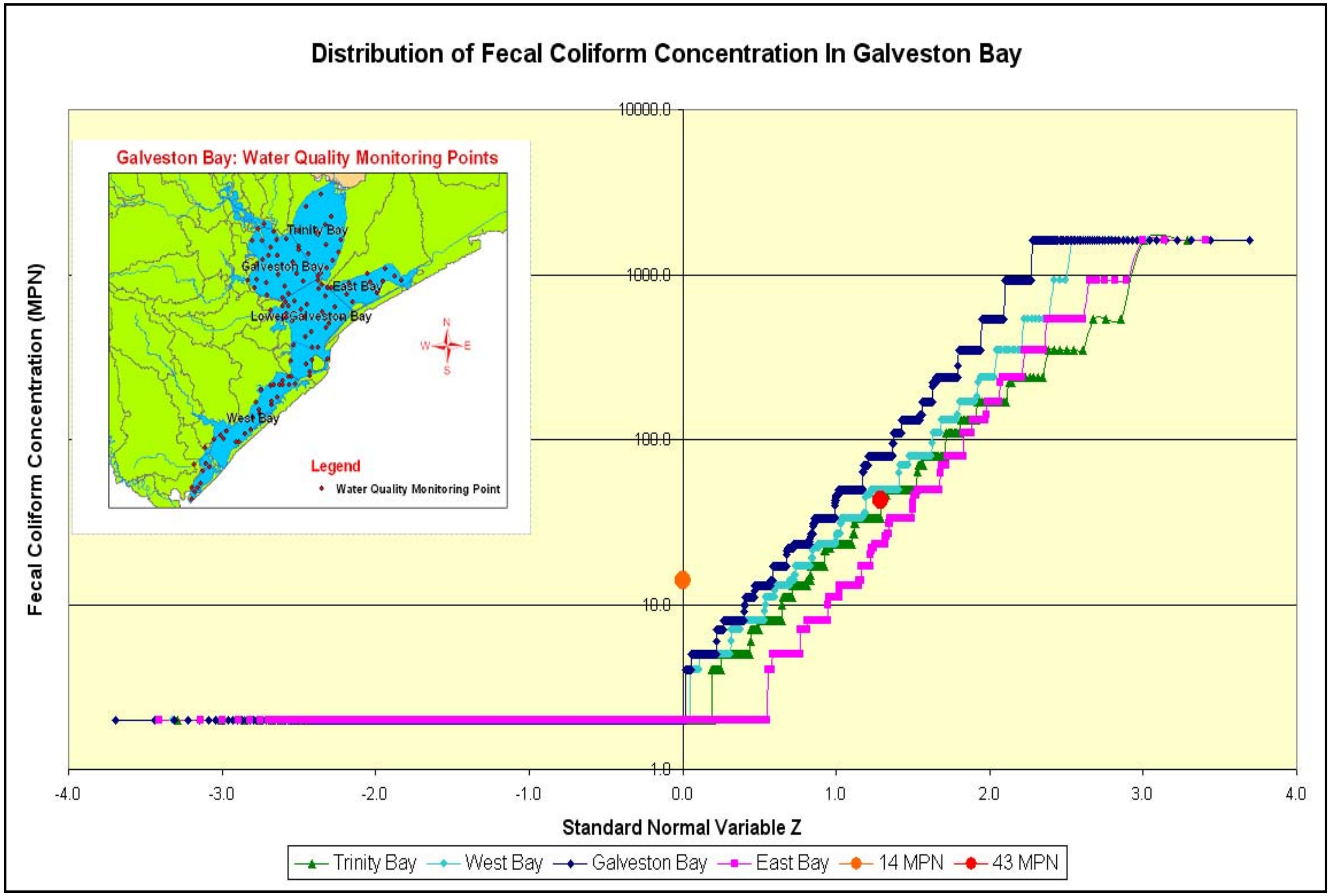


Figure 4.3.2: TDH monitoring dataset for fecal coliform in the impaired segments.

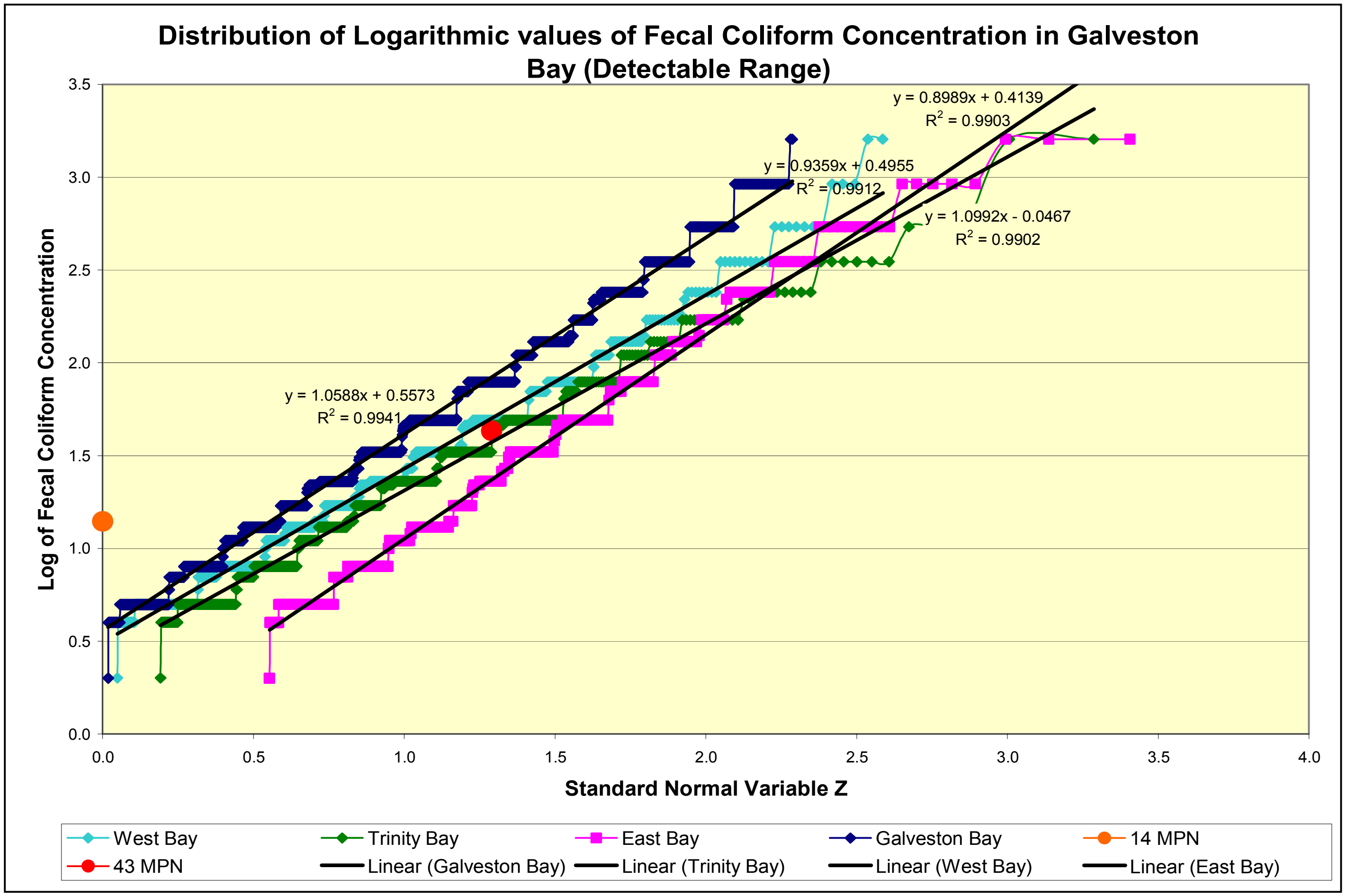


Figure 4.3.3: Log normal distribution observed in the detectable range of TDH monitoring dataset for fecal coliform in the impaired segments.

4.3.3 RESULT

Frequency analysis using frequency factor shows that (Figure 4.3.1) the median fecal coliform concentrations, which occurs at z = 0, do not exceed 14 MPN for all the four bay segments. The problem of not meeting this criterion occurs at individual stations rather in the entire bay as the combined dataset statistically complies with the criterion. The upper 10% of the sample, which occurs at z value of 1.29, exceeds 43 MPN in Galveston Bay and West Bay, is approximately 43 MPN in Trinity Bay and is below 43 MPN in East Bay.

In the detectable range of MPN sampling method (2 to 1600 cfu/100ml), the statistical distribution of fecal coliform dataset is consistent. Figure 4.3.3 shows that the concentration of bacteria in water in the detectable range follows a log normal distribution in all of the bay segments.

CHAPTER 5: ESTIMATION OF LOADINGS

5.1 Database Development and Arc Hydro for Study Area

5.1.1 METHODOLOGY

A geodatabase is a collection of geospatial data stored in a relational database. In a relational database, all data are stored in a set of tables linked by relationships, which are associations between records in connected tables through values in key fields that the tables share. Different hydrologic analyses and computation are made possible by utilizing these relationships (Maidment 2002).

The Arc Hydro framework, the simplest from of Arc Hydro, is utilized in this study for several calculations. The Arc Hydro framework has five feature classes to represent the hydro network, watersheds, water bodies, and monitoring points.

The Arc Hydro Framework is implemented in order to identify outlet junctions for each watershed, find downstream length of the hydro junctions to the estuary and to apply the Arc Hydro tools as necessary.

5.1.2 PROCEDURE OF APPLICATION

5.1.2.1 Generating the Geodatabase

A geodatabase is developed containing *Watershed* (drainage basin), *HydroEdge* (streams and channels), *Waterbody* (lakes, reservoirs, and estuary), *MonitoringPoint* (USGS Gaging stations) feature classes for the study area and the study area watershed. Descriptions of these data sets are available in Chapter 3 of this report. Development of the Geo-database requires defining the coordinate systems and the spatial extent of the feature-classes. The Texas State mapping System (TSMS) is applied to the geodatabase as its coordinate system.

As part of this study, centerlines were created through the middle of Houston ship channel, Lake Houston and other water bodies to create a continuous stream network. A few existing gaps in the stream network were also filled. A complete and continuous stream network is necessary for building geometric network in order to perform hydrologic analysis in ArcGIS.

5.1.2.2 Creation of HydroJunctions

Once the geodatabase is generated, a new empty point feature class *HydroJunction* is created importing the fields from *MonitoringPoint*. All the points of interest located on stream network, USGS stream gauge in this case, are loaded into *HydroJunction*. The *MonitoringPoint*s are snapped to the stream network, as they are loaded into *HydroJunction*. Snapping places the HydroJunctions on the stream network at a location closest to the

MonitoringPoint it is associated with. A HydroJunction is created in association with each *MonitoringPoint* and placed on the stream network in this process.

5.1.2.2.1 Creation of Outlet Junction for Watersheds

In order to generate Outlet Junctions for watersheds, *WshI* is generated by intersecting *HydroEdge* and *Watershed* with Geoprocessing Wizard. A geometric network is built from *WshI* to get *NetWshI_Junction*s with snapping. The generic Junctions are excluded from the *NetWshI_Junction*s by deleting them to get the Outlet Junctions. The Watershed Outlet Junctions are then loaded into the *HydroJunction*.

5.1.2.2.2 Populating FType Field of HydroJunction

Four different FTypes, which defines the type of junction, are assigned to the HydroJunctions. The *HydroJunction* FTypes are presented in Table 5.1.1.

	FType
1	Watershed Outlet
2	USGS Gauge
3	Stream Start Point
4	Stream End Point

Table 5.1.1: FTypes assigned to HydroJunctions

5.1.2.3 Assignment of HydroID to Feature Layers

HydroID is a feature identifier populated throughout the data model that is unique within a geodatabase. Once all feature layers required for this study are created, HydroIds are assigned to all layers so that relationships can be built between these features.

5.1.2.4 Building Geometric Network and Setting Flow Direction

A geometric network, which is a topologically connected set of edges and junctions, is built using the *HydroEdge* and *HydroJunction* feature classes. Flow direction is set for the network edges and corrections are made where necessary to make sure all the streams and channels are set to flow toward the estuary. Flowlines and shorelines in the stream network are identified. Most of the stream network for this study represents flowline as the streams outlining the water bodies are deleted and replaced with centerlines. Stream boundaries along Sabine lake are selected to set their Edgetype as shoreline and are disabled so flow does not occur along them.

5.1.2.5 Applying the Arc Hydro Schema

The Arc Hydro Framework without time series is applied to geodatabase by using the Schema wizard in ArcCatalog. The Schema creates the ArcHydro fields required to build relationship between feature classes. Once the Schema is applied, the geodatabase is ready for the application of ArcHydro tools.

The completed geodatabase after the application of Arc Hydro Framework is shown in Figure 5.1.1.

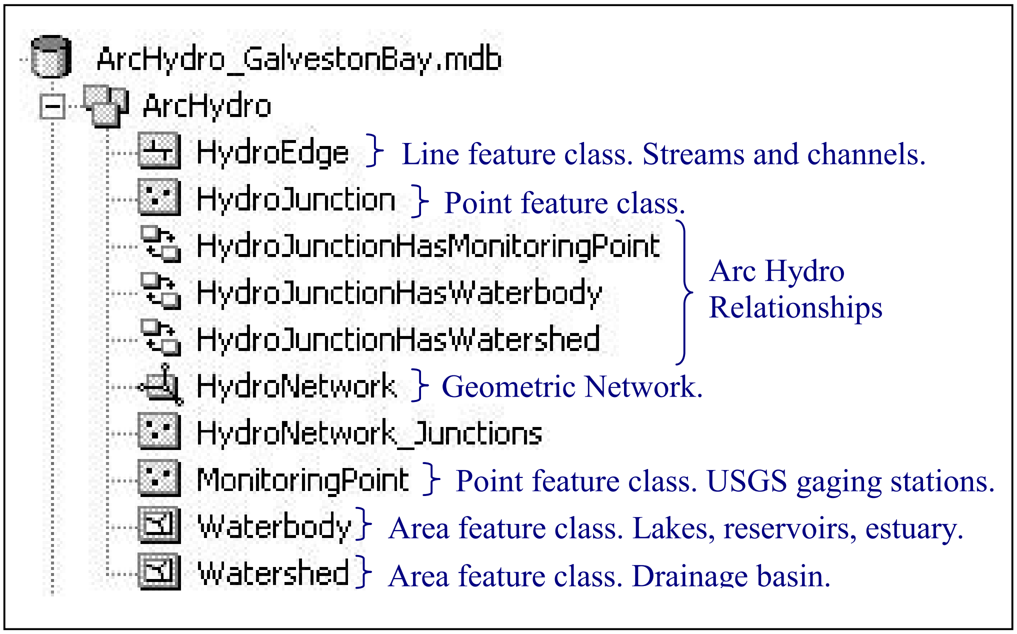


Figure 5.1.1: Geodatabase for Galveston Bay with Arc Hydro Framework

5.2 Estimation of Non-point Loadings from Watersheds

5.2.1 METHODOLOGY

The Galveston Bay Area is the receiving catchment for the San Jacinto River Basin, Trinity San Jacinto Coastal basin, and San Jacinto-Brazos Coastal Basin. Runoff from watersheds adjacent to the impaired segments flow directly to the bay. These watersheds are referred to as 'adjacent watershed' in this report. Watersheds located upstream of the impaired bay segments drain into streams and channels; and the runoff eventually flows into the bay are referred to as 'upstream watersheds'. Figure 5.2.1 presents the adjacent and upstream watershed area for this study.

Estimation of non-point loadings of fecal coliform from the adjacent and upstream watershed areas are computed as a product of runoff from the watersheds and Expected Mean Concentration (EMC) of each land use category. Upstream watershed load is decayed through the streams and channels to obtain the load reaching the estuaries. This procedure is described in section 5.3 of this report.

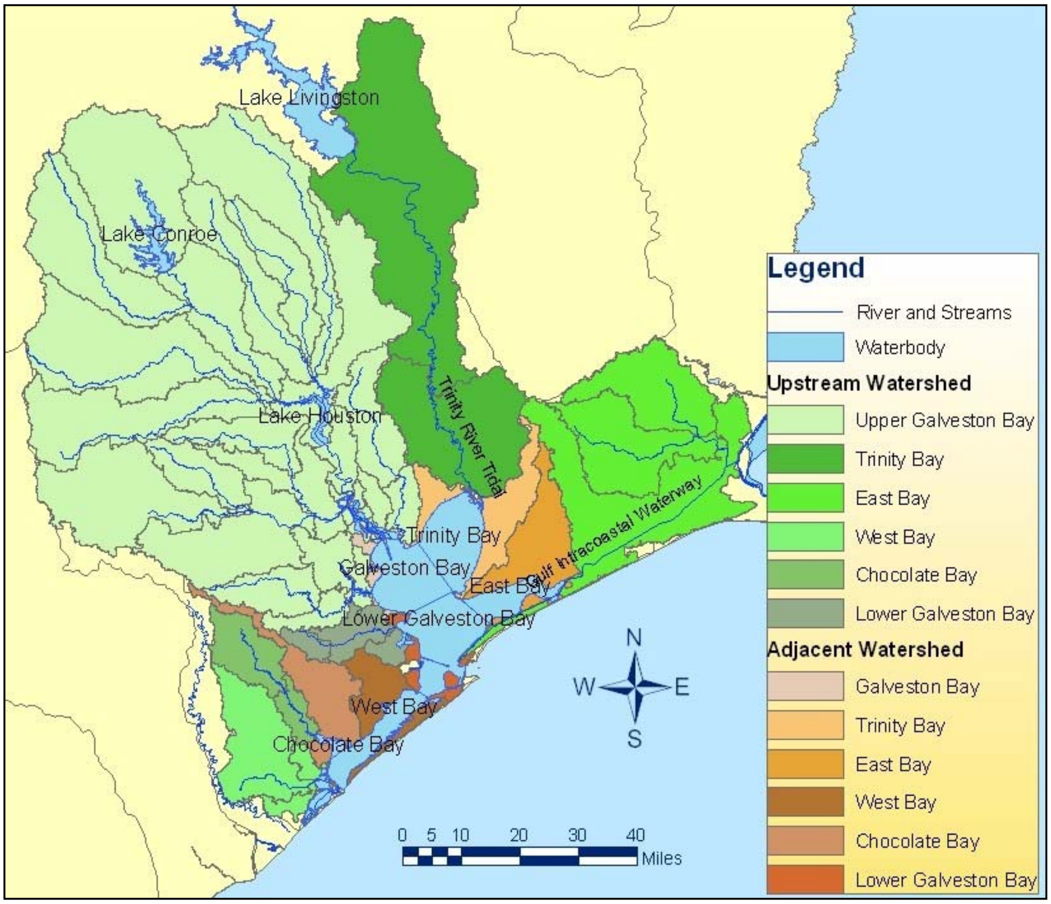


Figure 5.2.1: Adjacent and Upstream Watersheds in relation to the Impaired Segments

Areas of adjacent and upstream watershed segments draining to Galveston Bay, categorized by impaired bay segments they are draining to, are presented in Table 5.2.1

Table 5.2.1: Area of Adjacent and Upstream Watersheds draining to Galveston Bay

	Area of Adjacent Watershed (km^2)	Area of Upstream Watershed (km^2)	Number of Upstream Watershed Segments
Upper Galveston Bay (2421)	55.8	11575.7	30
Trinity Bay (2422)	433.8	3347.6	2
East Bay (2423)	493.1	2532.3	3
West Bay (2424)	298.3	770.8	4
Chocolate Bay (2432)	438.2	419.8	2
Lower Galveston Bay (2439)	99.3	351.2	4

The non-point loading analysis simulates pollutant load from a watershed area that drains to an impaired body of water using ArcGIS. The method is based on the capabilities of GIS tools to assess and perform calculations of concentrations and accumulated loads using watershed characteristics and hydrological data. The steps followed in this approach are: 1) determining the watershed draining into the impaired segments acquiring Digital elevation models of the region and processing to watershed delineation using GIS software, 2) collecting the mean annual precipitation data usually in grid format and generating a runoff grid or flow data using a mathematical relationship between rainfall-runoff based on hydrological and land use characteristics, 3) obtaining a land-cover and land-use coverage and translating it into a concentration coverage using Event Mean Concentration (EMC) which represent expected concentration values of constituents found in conventional land uses, and 4) finally the concentration grid is multiplied by the runoff grid to obtain the total annual load throughout the watershed (Quenzer and Maidment, 1998).

5.2.2 PROCEDURE OF APPLICATION

5.2.2.1 Preparation of Precipitation Data

The original PRISM National Precipitation Grid has a grid size of 4294 meter by 4294 meter, a unit of inch/year and is projected in Albers Equal Area projection. The precipitation grid obtained from PRISM database is masked to the project study area.

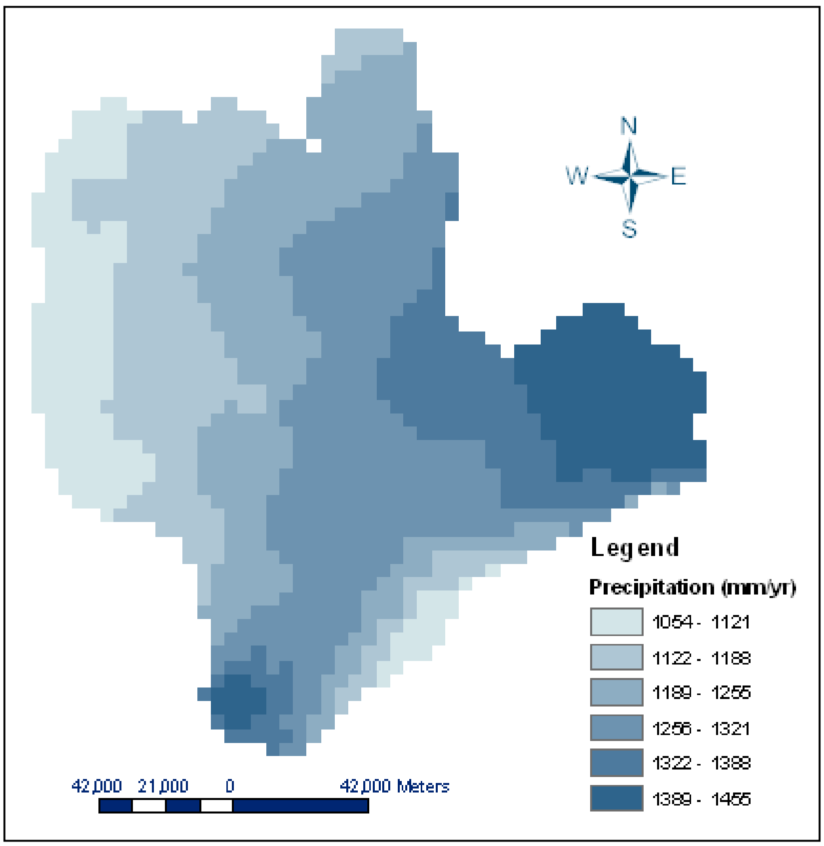


Figure 5.2.2: Mean Annual Rainfall Grid for Study Area

A five-kilometer buffer of the watershed area is created to mask the precipitation grid. Without the buffer the clipped grid excludes some of the watershed area. The precipitation grid is then masked to the buffered watershed area. The masked grid is then processed to a 30-meter by 30-meter grid and a mean annual rainfall grid with a unit of mm/yr is computed. The mean annual precipitation grid in mm for the study area is presented in Figure 5.2.2.

5.2.2.2 Rainfall-Runoff Relationship

Estimation of runoff is made using mathematical equations relating rainfall to runoff is taken from a previous study (Reed, Maidment and Patoux 1997). The study develops statistical relationship between rainfall and runoff by fitting a function that minimizes the sum of squared errors to observed data points in 90 watersheds in the state of Texas. The fitted function takes the following forms:

$$Q = 0.00064P\exp(0.0061P) \quad P < P_o \qquad (5.2.1)$$

$$Q = 0.510P - 3391 \quad P \geq P_o \qquad (5.2.2)$$

where Q is mean annual runoff and P is mean annual precipitation in mm/yr. The exponential function is fit to the drier area where mean annual rainfall is less than P_o (801 mm/yr). Average annual rainfall in the Galveston Bay study area ranged from 1150 to 1300 mm/yr. The linear function is used to derive runoff from the study area watershed.

5.2.2.3 Estimation of Runoff

The runoff per unit area grid in cubic meter per year is computed from the mean annual rainfall grid in mm using the raster calculator using the rainfall-runoff relationship in equation 5.2.1. The runoff per unit area grid is then multiplied by area of the grid (30m by 30 m) to get the estimation of runoff per grid cell in cubic meters per year.

5.2.2.4 Estimation of Flow from each Watershed

The runoff grid containing mean annual runoff in cubic meter per year from each 30 meter by 30-meter grid is summed for each watershed feature using the Zonal Statistics under Spatial Analyst.

5.2.2.5 Developing the EMC Grid

The Expected Mean Concentration or The EMC values for each land use category compiled by various sources are examined as discussed in section 3. The most appropriate EMC values for each land use categories are determined combining the EMC values obtained for the Galveston Bay area and professional judgment (Personal Communication: Dr. George Ward, Professor, University of Texas at Austin). An EMC table is then created with land-use code and EMC values with the appropriate EMC values. The project EMC values and their sources are presented in Table 5.2.2. Description of the source codes for the EMC values are presented in Table 5.2.3.

Table 5.2.2: Project EMC values

Land Use Code	Land Use Category	FC EMCs (colonies/ 100ml)	Source Code
1	Urban or built-up land	22000	NPS
11	Residential	22000	NPS
12	Commercial and services	22000	Inferred from NPS
13	Industrial	9700	CCBNEP
14	Transportation, communication, utilities	22000	Inferred from NPS
15	Industrial and commercial complexes	22000	Inferred from NPS
16	Mixed urban or built-up land	22000	NPS
17	Other urban or built-up land	22000	NPS
2	Agricultural land	2500	NPS
21	Cropland and pasture	2500	NPS
22	Orchards, groves, vineyards, nurseries, and ornamental horticulture	2500	Inferred from NPS
23	Confined feeding operations	5000	Judgment
24	Other agricultural land	2500	NPS
3	Rangeland	2500	Inferred from NPS
31	Herbaceous rangeland	2500	Inferred from NPS
33	Mixed rangeland	2500	Inferred from NPS
4	Forest land	1000	Judgment
41	Deciduous forest land	1000	Judgment
42	Evergreen forest land	1000	Judgment
43	Mixed forest land	1000	Inferred, Judgment
5	Water	0	NPS, Judgment
51	Streams and canals	0	NPS, Judgment
52	Lakes	0	NPS, Judgment
53	Reservoirs	0	NPS, Judgment
54	Bays and estuaries	0	NPS, Judgment
6	Wetland	200	Judgment
61	Forested wetland	200	Judgment
62	Nonforested wetland	200	Judgment

Table 5.2.3: Description of source code for project EMC values

Source	Description
NPS	Galveston Bay National Estuary Program Non-point Source Characterization (NPS) study
CCBNEP	Corpus Christi Bay National Estuary Program (CCBNEP) study
Inferred	Value inferred from observed data for similar land use category in Galveston Bay area due to lack of data for the specific land use category in Galveston bay area.
Judgment	Professional Judgment by Dr. George Ward, Professor, University of Texas at Austin

Once the EMC table is created, the EMC values are incorporated into the land use coverage by joining the land use coverage file and the EMC table using land use code. The EMC grid is created by converting the EMC attributes of land use coverage feature in to raster. Figure 5.2.3 shows the EMC grid for study area.

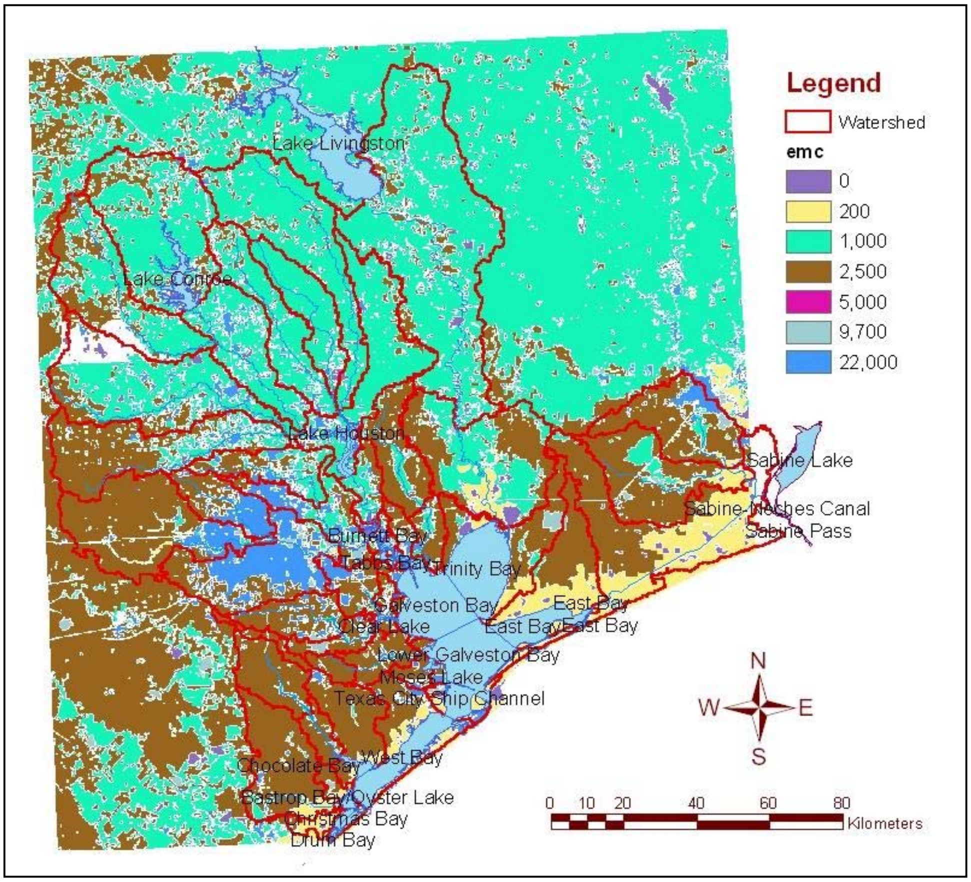


Figure 5.2.3: EMC Grid for study area

5.2.2.6 Estimation of Non-Point Loading

The study area runoff grid is multiplied by the EMC grid to compute the non-point loading grid. The sum of pollutant loadings for each watershed segment is computed by summing the grids located in watershed boundary. This process is done by using Zonal Statistics under Spatial Analyst. Once the loading for each watershed segment is computed, computation process for non-point loadings for watershed adjacent to the impaired segments is complete. Annual load generated from the watershed segments is presented in Figure 5.2.4.

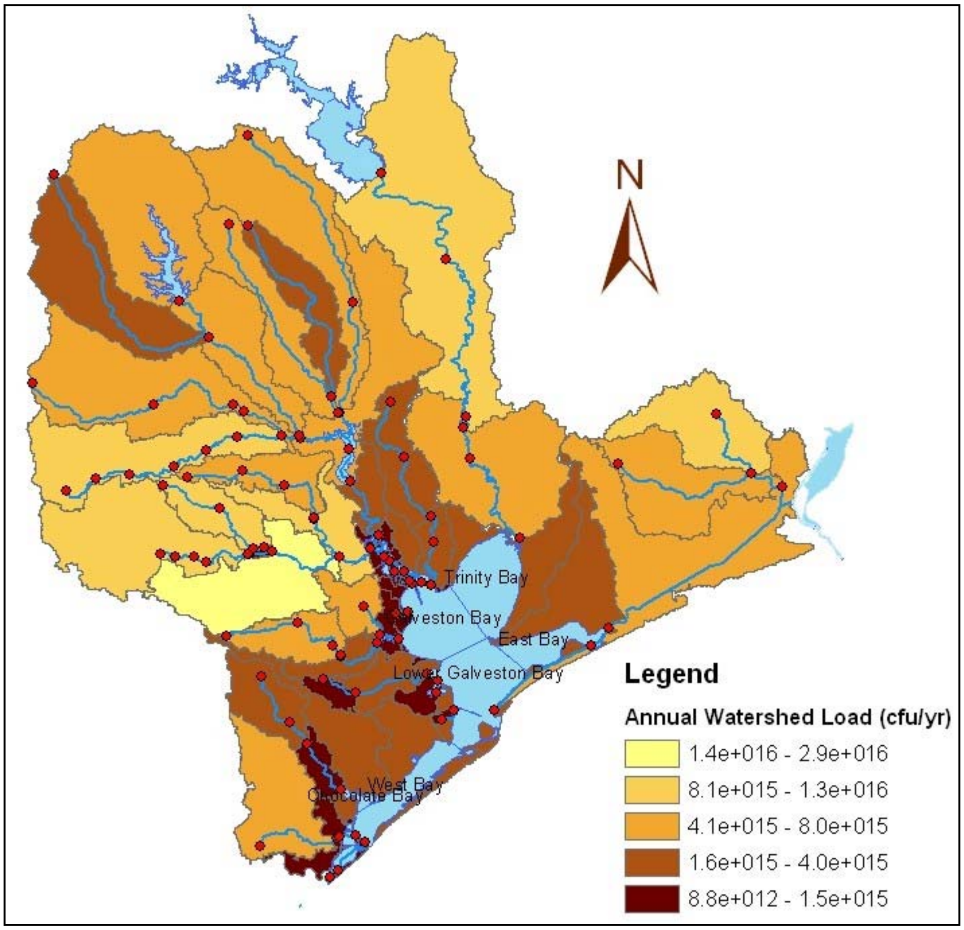


Figure 5.2.4: Annual Non-Point fecal coliform loadings from watershed Segments

Corresponding fecal coliform concentration in loads from adjacent watershed segments draining to each bay segment is computed by diving the load by runoff flow (Equation 5.2.3).

Concentration (cfu/100ml) = Annual FC Load (cfu/yr) / [Runoff (m3/year) × 10000] (5.2.3)

5.2.3 RESULT

5.2.3.1 Non-Point Fecal Coliform Loadings from Adjacent Watershed

Table 5.2.4 presents runoff flow and non-point fecal coliform loadings from watershed adjacent to the impaired segments.

Table 5.2.4: Runoff flow and Non-point Loadings from Adjacent Watersheds

	Area of Adjacent Watershed (km^2)	Runoff from Adjacent Watershed (m^3/yr)	Annual FC Load (cfu/yr)	Corresponding Fecal Coliform Concentration (cfu/100ml)
Upper Galveston Bay (2421)	55.8	1.74E+07	1.55E+15	8908
Trinity Bay (2422)	433.8	1.43E+08	3.77E+15	2636
East Bay (2423)	493.1	1.55E+08	2.52E+15	1626
West Bay (2424)	298.3	8.16E+07	3.30E+15	4044
Chocolate Bay (2432)	438.2	1.34E+08	3.91E+15	2918
Lower Galveston Bay (2439)	99.3	2.58E+07	2.03E+15	7868

5.3 Decaying Non-point Load from Upstream Watersheds

5.3.1 METHODOLOGY

Fecal coliform, as discussed in Chapter 2, has a high decay rate. Thus, there is a significant loss of fecal coliform colonies from upstream watersheds as they travel through the streams to enter the Galveston Bay system. Watershed loads from the upstream watersheds are decayed along the streams to determine the final fecal coliform loads entering the Galveston Bay system.

Any large reservoir or lake retains contaminants as the contaminants flow through the reservoir or lake. A significant portion of watershed draining into the Upper Galveston Bay for this study drains into Lake Houston and subsequently drains into the Upper Galveston Bay through San Jacinto River and Houston Ship Channel. While decaying fecal colifom loadings generated from watershed segments upstream to Lake Houston, retention in Lake Houstion is considered.

The decayed concentration of fecal coliform traveling along a stream or a channel can be computed using travel time along the streams in the direction of the flow and bacterial decay rate. The relationship used to determine the decayed concentration is:

$$C = C_0 \exp(-K_B * t) \qquad (5.3.1)$$

where C is the decayed concentration, C_0 is the initial concentration, K_B is the overall first order decay rate and t is the time of flow (Thomann and Mueller 1987).

Travel time is found as distance traveled divided by velocity of flow.

$t = X/v$ (5.3.2)

where X is the distance traveled and v is the velocity of flow.

Load is computed as a product of flow and concentration. For a specific watershed load, the relationship becomes:

$L = L_0 * \exp(-K_B * X/v)$ (5.3.3)

where L is the decayed load, L_0 is initial load from watershed, K_B is the overall first order decay rate, X is the distance traveled and v is the velocity of flow.

Figure 5.3.1 shows the upstream watersheds for Trinity Bay, watershed outlet for an upstream watershed (Point A) and the HydroJunction at the mouth of the estuary (Point B). Watershed load from the upstream watershed is decayed for the distance from A to B using the relationship in equation 5.3.2.

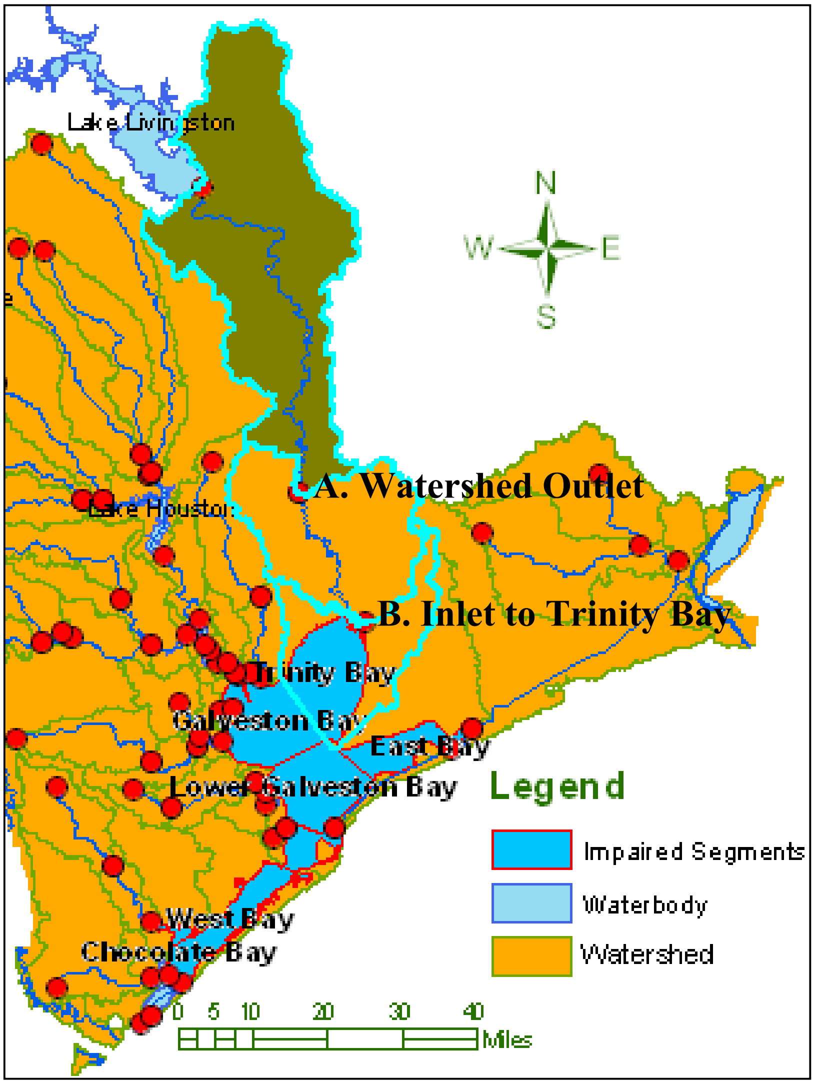


Figure 5.3.1: Upstream watersheds for the Trinity Bay

5.3.2 Procedure of Application

Each watershed is linked to a HydroJunction through an Arc Hydro relationship, using the watershed outlet for that specific watershed. Loadings from the watershed can be consolidated to that specific HydroJunction. The length from each watershed outlet to the mouth of the estuary is computed and the load is decayed for that length. The decayed load is then summed up or accumulated at the HydroJunctions located at the mouth of the estuary for each bay segment.

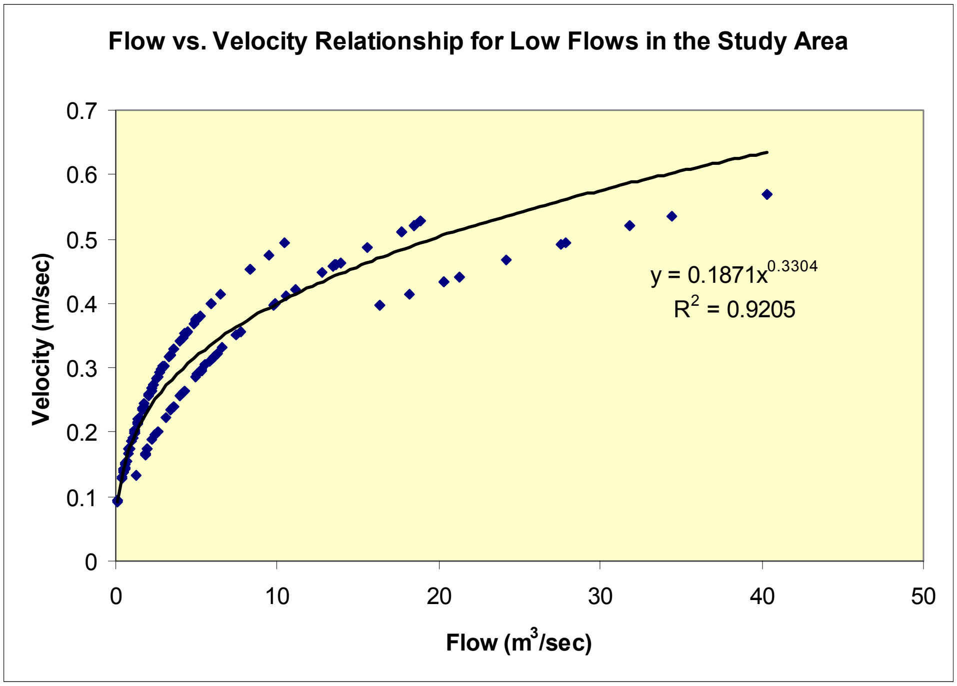
5.3.2.1 Calculating Length Downstream

The downstream length to from each watershed outlet to the impaired segment in Galveston Bay is calculated using 'Calculate Length Downstream for Junctions' tool in under attribute tool in the ArcHydro toolkit. The HydroJunctions located on the edges of impired segments are set sink for this task.

The function Calculate Length Downstream for Junctions calculates the length from a network junction to the sink that the junction flows to, and populates the field LengthDown in that feature class with the calculated value. The tool works by tracing downstream from a given feature and summing up the lengths of all downstream edges that comprise the shortest path between the feature and the nearest sink. (See ArcHydro help manual)

5.3.2.2 Flow – Velocity Relationship in Stream

Velocities in the streams are required to determine the decayed load from the upstream watershed for the entire study area. The relationship between flow and velocity is derived using EPA Reach File 1 (RF1) database. The RF1 database documents flow and velocity for the entire United States. The RF1 reach file is clipped using the study area watershed in order to extract the reaches for study area. Relationship between the flow and velocity is derived from the study area by fitting regression line to the attribute values contained in RF1 data (Figure 5.3.2). A regression function minimizes the sum of squared errors between the points and fitted line.



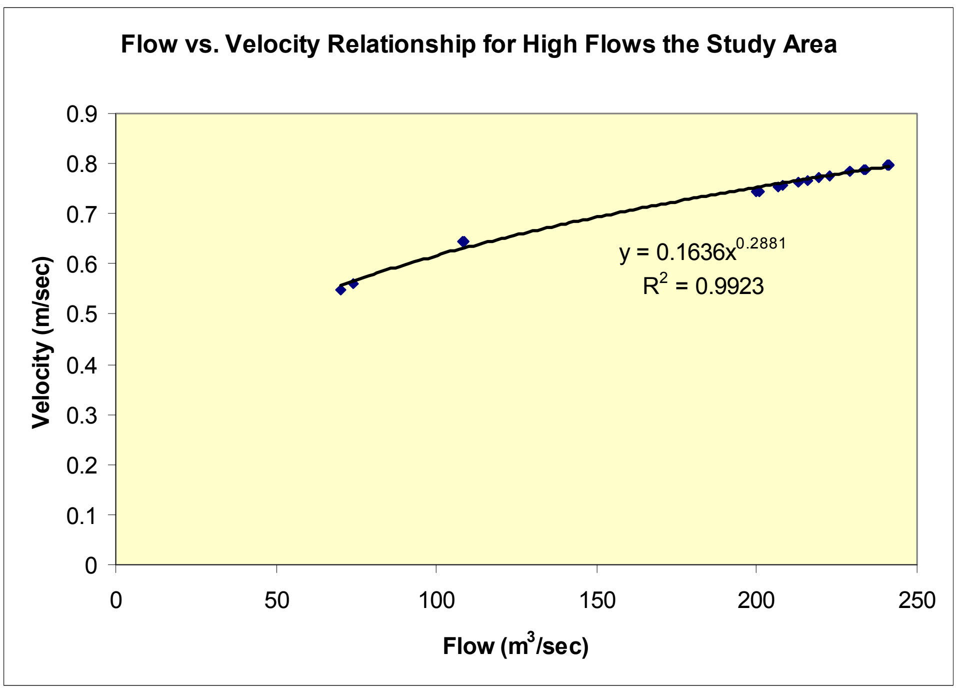


Figure 5.3.2: Stream Flow vs. Velocity in the Study Area Streams

The regression equations fitted to the dataset are as follows:

$$V = 0.1871Q^{0.3304}{}_{when Q \leq 50 m^3/\sec}$$
$$V = 0.1636Q^{0.2281}{}_{when Q > 50 m^3/\sec}$$

where Q stream flow (m^3/sec) and V is velocity (m/sec). It turns out that the dataset is better fitted when separate regression functions are used for the low flows (≤ 50 m^3/sec) and high flows (> 50 m^3/sec).

Estimated stream flow in the study area watershed ranges from 0.04 m^3/sec to 85 m^3/sec. The estimated stream flows result from accumulated runoff from surrounding watershed areas. These flow estimations are appropriate for non-point loading calculations. However, they fail to account for the upstream flow the streams might receive such as discharge into Trinity River from Lake Livingston. Estimated stream flows and velocities are checked against the reach file dataset and also the USGS stream gauge stream flow data in order to identify any large discrepancies.

It was found that the stream flow and velocity in the Trinity River was significantly higher than the estimated runoff value. The discrepancy is reasonable considering the fact that Trinity River receives flow from upstream and Lake Livingston. The estimated runoff value accounts for only surrounding watersheds not the upstream flow.

To allow for this limitation, adjustments in flow and velocity values have been made for the Trinity River. The average mean annual flow is taken from the USGS stream gauge upstream. The velocity in Trinity River is replaced with the flow velocity from the Reach file, which is 2.6 m/sec.

5.3.2.3 Computation of Decayed Load

Once the distance from each watershed outlet to the mouth of the estuary and velocity along the streams are computed, decayed load at each watershed outlet is computed using relationship stated in the methodology section. A overall first order decay of 1.5 day^{-1} cited for river water at 20^{0}C (Bogosian et al. 1996) is used for decay computation. Decayed load for each watershed segments along with different parameters required for computation of decayed load (downstream length, JunctionID, flow along channel, velocity along channel) are attached as Appendix F.

5.3.2.4 Retention of Fecal Coliform Load in Lake Houston

In order to account for the retention of fecal coliform in Lake Houston, residence time in the lake is added to travel times of outflows from the watersheds located upstream of Lake Houston. Figure 5.3.3 shows the upstream watershed segments draining through Lake Houston. Load passing through these segments are reduced by retention in Lake Houston.

Figure 5.3.3: Upstream Watershed Segments Passing through Lake Houston

Volume of Lake Houston was available from The Texas Water Development Board (TWDB)'s website from their reservoir volumetric surveys. Conservation storage capacity of Lake Houston obtained from the TWDB website is 1.589 × 108 m3 (128, 863 acre-Feet). Survey date for this data value is March of 1994. Total approximated flow out of Lake Houston obtained from runoff accumulation for this study is 60.2 m3 / sec (2124 ft3 / sec). Residence time in Lake Houston in computed as the volume of the lake divided by flow rate through the lake.

$$
\begin{aligned}
\text{Residence time, } t_d &= V / Q \\
&= 1.589 \times 108 \text{ m3} / 60.2 \text{ m3} / \text{sec} \\
&= 30.58 \text{ days}
\end{aligned}
$$

where V is the volume of the lake and Q is flow rate.

This residence time (approximately 30.6 days) is added to travel times of outflows from the watersheds located upstream of Lake Houston. Computation of decayed non-point loadings from watershed segments located upstream of Lake Houston is presented in Table 5.3.1

Once the residence time in Lake Houston is added to the travel time of loads generated from watershed located upstream of Lake Houston to Galveston Bay, the resulting load that reaches Galveston Bay becomes zero or very insignificant with the decay rate of 1.5 day^{-1}. Thus, it is found that loads from upstream watershed are retained in Lake Houston.

Table 5.3.1: Decayed Annual Fecal Colirom Load from Watersheds Upstream to Lake Houston with and without Retention in Lake Houston

Watershed Segment	Area (km^2)	Annual Load (cfu/yr)	Down-stream Length (km)	Without Retention in Lake Houston			With Retention in Lake Houston			Reduction in Decayed Load (cfu/yr)
				Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	
1002	776.0	6.17E+15	47.1	1.02	1.33E+15	78%	31.6	1.59E-05	100%	1.33E+15
1003	1012.5	4.07E+15	68.9	2.07	1.83E+14	95%	32.6	2.20E-06	100%	1.83E+14
1004	570.1	6.42E+15	75.4	1.73	4.78E+14	93%	32.3	5.74E-06	100%	4.78E+14
1008	1133.4	7.62E+15	75.3	1.44	8.79E+14	88%	32.0	1.05E-05	100%	8.79E+14
1009	842.5	8.27E+15	80.4	2.71	1.43E+14	98%	33.3	1.71E-06	100%	1.43E+14
1010	558.0	4.41E+15	68.9	2.09	1.93E+14	96%	32.7	2.31E-06	100%	1.93E+14
1011	404.3	2.32E+15	74.8	2.99	2.63E+13	99%	33.6	3.15E-07	100%	2.63E+13
1012	1160.0	4.96E+15	138.7	4.18	9.34E+12	100%	34.8	1.12E-07	100%	9.34E+12
1015	852.9	3.44E+15	120.7	4.06	7.77E+12	100%	34.6	9.32E-08	100%	7.77E+12
Total					**3.25E+15**			**3.90E-05**		**3.25E+15**

5.3.2.5 Consolidation and Accumulation of Decayed Load

Each watershed is linked to a HydroJunction through Arc Hydro relationship, which is the watershed outlet for that specific watershed. Loadings from the watershed can be consolidated to that specific HydroJunction. Length of each watershed outlet to the mouth of the estuary is computed and the load is decayed for that length. The decayed load is then summed up or accumulated at the HydroJunctions located at the mouth of the estuary for each bay segment.

Decayed fecal coliform loads are summed at all the watershed outlets and the stream end points using the ‘Consolidate Attribute’ tool in the ‘Attribute Tools’ of ArcHydro toolset.

The Consolidate Attributes tool (Attribute Tools menu) allows consolidating the source attribute in the source layer based on a relationship between the source layer and the target layer. Only layers having relationships may be selected as target or source layer. The source has to be different from the target, and related to it. In this case, the source attribute is decayed load in the Watershed layer and the target layer is consolidated load in the *HydroJunction* feature class.

The ArcHydro relationship that enables the Consolidate function to work is that JunctionID in the Watershed feature layer has to be same as HydroID in *HydroJunction* feature layer. In order for the Consolidate function to work the JunctionID in the Watershed feature layer is populated by manually inputting

HydroID of the watershed outlet junction into the JunctionID field of a specific watershed.

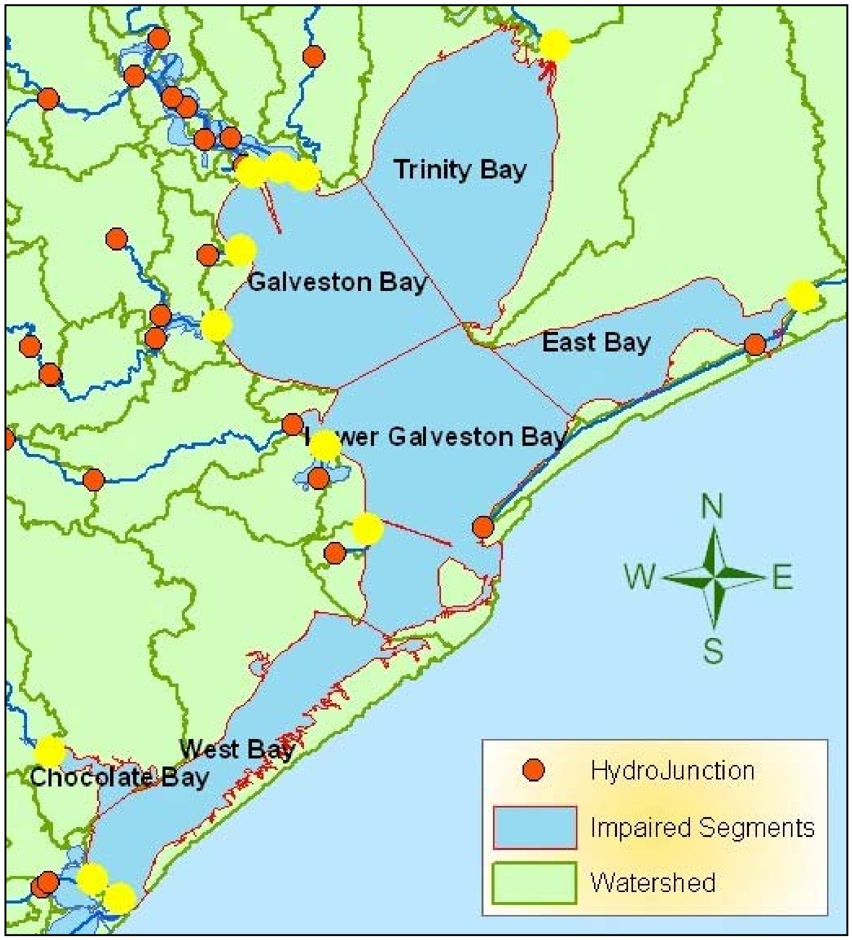


Figure 5.3.4: HydroJunctions located on the Edges of Impaired Bay Segments (yellow circles)

The consolidated loads are then accumulated to the HydroJunctions located at the edges of the impaired bay segments (Figure 5.3.4). The function Accumulate Attributes (Attribute Tools menu) accumulates 'Consolidated Load' attribute of the

‘*HydroJunction*’ feature class located upstream of source ‘HydroJunction’ points. The source ‘HydroJunction’ points are the ones located on the edges of the impaired bay segments. The accumulated decayed load from upstream watershed segments enters the impaired segments at these locations. They represent non-point loadings draining to the bay segments through different streams and channels. These loads are indicated as ‘Decayed Load’ or non-point loadings from upstream watershed.

5.3.2.6 Consolidation and Accumulation of Runoff Flow

Runoff flow generated from each watershed is consolidated at the watershed outlets in the same manner as the load consolidation. The flow is, thus, transferred to the stream network. The consolidated runoff flows are then accumulated to the HydroJunctions located at the edges of the impaired bay segments. These runoff flows are indicated as flow from upstream watershed.

Fecal coliform loads and flow generated from upstream watershed segments of East Bay are adjusted to account for the loads and runoff flow to Sabine Lake. An adjustment factor of 0.5 is used with an assumption that half of the flow generated from the watersheds upstream to East Bay flows to West Bay, and the rest drains to Sabine Lake.

5.3.3 RESULT

5.3.3.1 Non-Point Loadings from Each Upstream Watershed Segments

Figure 5.3.5 presents decayed annual fecal coliform load from watershed segments upstream of Galveston Bay that reaches the impaired bay segments. The watershed segments are labeled with Texas Commission on Environmental Quality (TCEQ) water quality segment number.

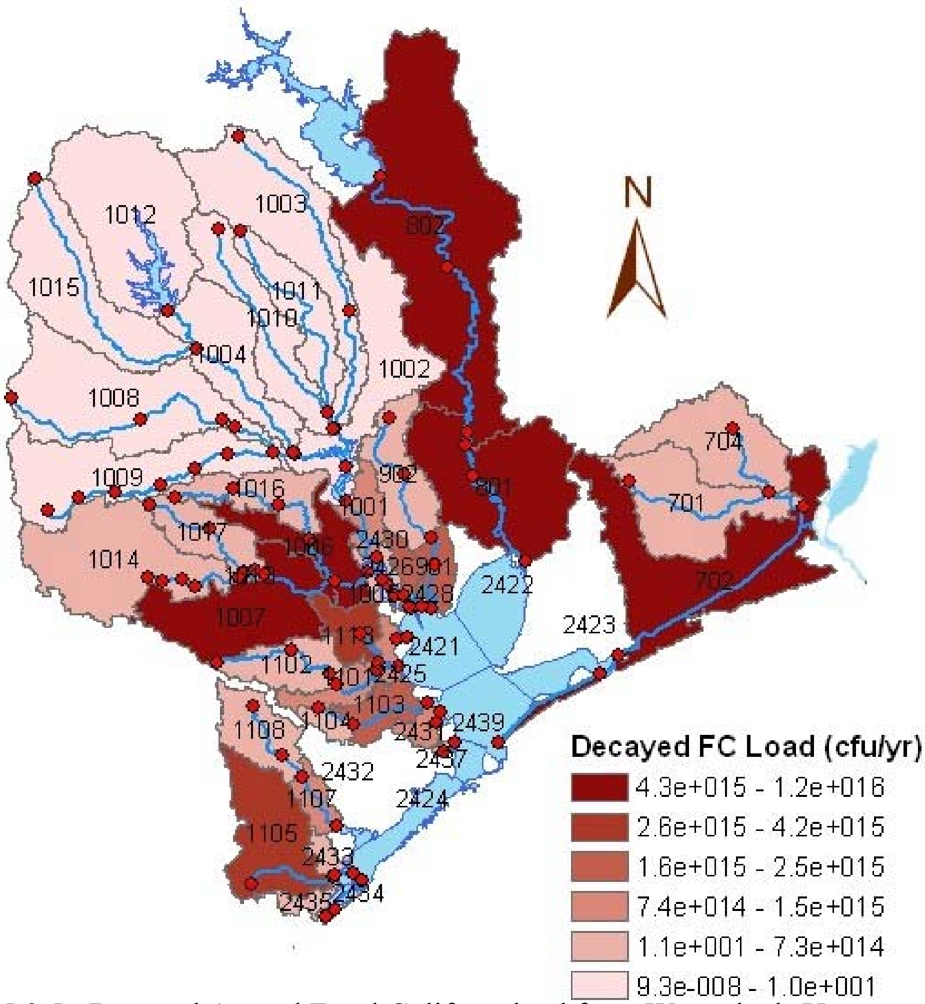


Figure 5.3.5: Decayed Annual Fecal Coliform load from Watersheds Upstream of Galveston Bay

In Upper Galveston Bay, Houston Ship Channel (1006) and Houston Ship Channel (Buffalo Bayou) are the largest contributors of non-point fecal coliform load from upstream watershed.

Decayed fecal coliform load from the watershed segments located upstream of each impaired segment in Galveston Bay is presented in Tables5.3.2 to 5.3.7. The upstream watershed segments are represented with their Texas Commission on Environmental Quality (TCEQ) water quality segment number. Retention time in Lake Houston is accounted for in computation of decayed load from upstream watershed segments into Upper Galveston Bay. Percent of total upstream non-point loadings contribution from each segment is shown in the last column of the table. This percentage value shows relative contribution of different watershed segments.

5.3.3.2 Non-Point Loadings categorized by Channels and Streams

Accumulated fecal coliform loads and flows from upstream watershed segments at HydroJunctions located at the boundaries of impaired segments represent non-point loadings draining to the bay segments through different streams and channels. They are presented in Table 5.3.8. Percentage of loads entered through each stream segment to each impaired bay segments in also shown.

Table 5.3.2: Non-point loadings from Upstream Watershed Segments draining to Upper Galveston Bay (2421)

(Computation of travel time and decayed load accounts for retention in Lake Houston)

Watershed Segment	Watershed Area (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time with Retention Time in Lake Houston (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
901	143.0	4.68E+07	1.85E+15	0.0	0.00	1.8E+15	0%	5.69%
902	387.2	1.24E+08	3.01E+15	28.8	1.13	5.5E+14	82%	1.69%
1001	160.4	5.08E+07	1.81E+15	18.8	0.40	9.9E+14	45%	3.04%
1002	776.0	2.40E+08	6.17E+15	47.1	31.60	1.6E-05	100%	0.00%
1003	1012.5	2.82E+08	4.07E+15	68.9	32.65	2.2E-06	100%	0.00%
1004	570.1	1.56E+08	6.42E+15	75.4	32.31	5.7E-06	100%	0.00%
1005	45.2	1.45E+07	6.54E+14	0.0	0.00	6.5E+14	0%	2.01%
1006	361.2	1.08E+08	1.04E+16	15.7	0.35	6.1E+15	41%	18.94%
1007	759.6	2.12E+08	2.91E+16	25.8	0.60	1.2E+16	60%	36.30%
1008	1133.4	2.69E+08	7.62E+15	75.3	32.02	1.1E-05	100%	0.00%
1009	842.5	1.99E+08	8.27E+15	80.4	33.29	1.7E-06	100%	0.00%
1010	558.0	1.56E+08	4.41E+15	68.9	32.67	2.3E-06	100%	0.00%
1011	404.3	1.18E+08	2.32E+15	74.8	33.57	3.2E-07	100%	0.00%
1012	1160.0	2.77E+08	4.96E+15	138.7	34.76	1.1E-07	100%	0.00%
1013	12.2	3.52E+06	7.12E+14	48.0	1.42	8.5E+13	88%	0.26%
1014	917.5	2.13E+08	1.14E+16	55.7	1.83	7.3E+14	94%	2.24%
1015	852.9	1.99E+08	3.44E+15	120.7	34.64	9.3E-08	100%	0.00%
1016	330.7	9.07E+07	5.27E+15	44.7	1.95	2.8E+14	95%	0.87%
1017	289.9	7.77E+07	9.29E+15	51.4	2.36	2.7E+14	97%	0.83%
1101	140.4	4.26E+07	2.35E+15	7.4	0.29	1.5E+15	35%	4.70%

Watershed Segment	Watershed Area (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time with Retention Time in Lake Houston (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
1102	289.5	8.57E+07	4.60E+15	28.1	1.25	7.1E+14	85%	2.18%
1113	189.5	5.93E+07	5.10E+15	6.1	0.31	3.2E+15	37%	9.92%
2425	76.2	2.39E+07	1.34E+15	0.4	0.01	1.3E+15	2%	4.06%
2426	91.6	2.99E+07	1.96E+15	0.0	0.00	2.0E+15	0%	6.05%
2427	19.2	6.17E+06	2.08E+14	5.7	0.61	8.4E+13	60%	0.26%
2428	6.0	1.94E+06	1.34E+14	5.5	0.85	3.8E+13	72%	0.12%
2429	13.2	4.25E+06	2.86E+14	9.5	0.80	8.6E+13	70%	0.27%
2430	25.1	8.17E+06	6.37E+14	11.3	1.09	1.2E+14	81%	0.38%
2436	4.5	1.43E+06	4.54E+13	1.1	0.19	3.4E+13	25%	0.10%
2438	3.9	1.24E+06	2.57E+13	0.0	0.00	2.6E+13	0%	0.08%
Total	**11575.7**	**3.10E+09**				**3.2E+16**		**100.00%**

Table 5.3.3: Non-point loadings from Upstream Watershed Segments draining to Trinity Bay (2422)

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
801	1024.7	3.52E+08	7.0E+15	0.0	0.00	7.0E+15	0%	47.14%
802	2322.9	7.13E+08	1.1E+16	55.1	0.24	7.8E+15	31%	52.86%
Total	**3347.6**	**1.06E+09**				**1.5E+16**		**100.00%**

Table 5.3.4: Non-point loadings from Upstream Watershed Segments draining to East Bay (2423)

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
701	667.4	2.56E+08	6.5E+15	62.3	1.57	6.2E+14	91%	8.27%
702	1291.0	4.68E+08	6.5E+15	0.0	0.00	6.5E+15	0%	86.98%
704	574.0	2.24E+08	1.3E+16	74.2	2.40	3.5E+14	97%	4.75%
Total	**2532.3**	**9.48E+08**				**7.4E+15**		**100.00%**

Table 5.3.5: Non-point loadings from Upstream Watershed Segments draining to West Bay (2424)

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
1105	580.8	2.00E+08	5.4E+15	5.2	0.17	4.2E+15	23%	88.27%
2433	75.8	2.49E+07	5.0E+14	0.0	0.00	5.0E+14	0%	10.53%
2434	36.6	1.10E+07	8.8E+12	0.0	0.00	8.8E+12	0%	0.19%
2435	77.7	2.61E+07	1.5E+14	11.4	0.75	4.8E+13	67%	1.01%
Total	**770.8**	**2.62E+08**				**4.7E+15**		**100.00%**

Table 5.3.6: Non-point loadings from Upstream Watershed Segments draining to Chocolate Bay (2432)

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
1107	113.6	3.67E+07	1.1E+15	0.0	0.00	1.1E+15	0%	63.98%
1108	306.2	8.83E+07	2.3E+15	20.3	0.89	6.0E+14	74%	36.02%
Total	**419.8**	**1.25E+08**				**1.7E+15**		**100.00%**

Table 5.3.7: Non-point loadings from Upstream Watershed Segments draining to Lower Galveston Bay (2439)

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	Down-stream Length (km)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay	Percent of Total Upstream Load
1103	185.4	5.66E+07	2.5E+15	0.0	0.00	2.5E+15	0%	65.02%
1104	73.5	2.21E+07	6.5E+14	23.9	1.66	5.4E+13	92%	1.42%
2431	77.5	2.33E+07	1.3E+15	3.1	0.21	9.6E+14	27%	25.39%
2437	14.7	4.13E+06	3.3E+14	0.4	0.05	3.1E+14	7%	8.18%
Total	**351.2**	**1.06E+08**				**3.8E+15**		**100.00%**

Table 5.3.8: Accumulated Non-Point Fecal Coliform Loads and Flows from Upstream Watershed Segments

Bay Name	DrainingFrom	Accumulated Flow (m^3/yr)	Accumulated Load (cfu/yr)	Percentage Load
Upper Galveston Bay (2421)	Clear Lake, Clear Bayou Tidal, Armand Bayou Tidal	2.12E+08	6.06E+15	19.1%
Upper Galveston Bay (2421)	Cedar Bayou Tidal	1.71E+08	2.40E+15	7.6%
Upper Galveston Bay (2421)	Houston Ship Channel, San Jacinto River	2.69E+09	2.13E+16	67.0%
Upper Galveston Bay (2421)	Tabbs Bay	3.19E+07	2.00E+15	6.3%
Upper Galveston Bay (2421)	Bayport Channel	1.24E+06	2.57E+13	0.1%
Total		3.10E+09	3.18E+16	100.0%
Trinity Bay (2422)	Trinity River	1.06E+09	1.48E+16	100.0%
Total		1.06E+09	1.48E+16	100.0%
East Bay (2423)	Gulf Intracoastal Waterway	4.74E+08	3.72E+15	100.0%
Total		4.74E+08	3.72E+15	100.0%
West Bay (2424)	Bastrop Bay/ Oyster Lake	2.25E+08	4.66E+15	98.8%
West Bay (2424)	Christmas Bay	3.72E+07	5.65E+13	1.2%
Total		2.62E+08	4.71E+15	100.0%

Bay Name	DrainingFrom	Accumulated Flow (m^3/yr)	Accumulated Load (cfu/yr)	Percentage Load
Lower Galveston Bay (2439)	Moses Lake watershed	2.33E+07	9.62E+14	25.4%
Lower Galveston Bay (2439)	Texas City Ship Channel	4.13E+06	3.10E+14	8.2%
Lower Galveston Bay (2439)	Dickinson Bayou	7.88E+07	2.52E+15	66.5%
Lower Galveston Bay (2439)	Gulf IntraCoastal Waterway	0.00E+00	0.00E+00	0.0%
Total		1.06E+08	3.79E+15	100.0%
Chocolate Bay (2432)	Chocolate Bayou	1.25E+08	1.67E+15	100.0%
Total		1.25E+08	1.67E+15	100.0%

5.3.3.3 Total Non-Point Loadings from Upstream Watershed Segments

Estimated total runoff flow and non-point loading of fecal coliform from upstream watershed is presented in Table 5.3.9.

Table 5.3.9: Runoff flow and Non-point Loadings from Upstream Watershed:

	Area of Upstream Watershed (km^2)	Runoff from Upstream Watershed (m^3/yr)	Annual FC Load (cfu/yr)	Corresponding Fecal Coliform Concentration (cfu/100ml)
Upper Galveston Bay (2421)	11575.7	3.10E+09	3.18E+16	1024
Trinity Bay (2422)	3347.6	1.06E+09	1.53E+16	1443
East Bay (2423)	2532.3	4.74E+08	3.72E+15	785
West Bay (2424)	770.8	2.62E+08	4.71E+15	1798
Chocolate Bay (2432)	419.8	1.25E+08	1.67E+15	1336
Lower Galveston Bay (2439)	351.2	1.06E+08	3.79E+15	3575

5.4 Estimation of Load from Lake Houston and Lake Livingston

5.4.1 FECAL COLIFORM LOAD FROM LAKE HOUSTON

In order to allow for the fecal coliform load flowing out of Lake Houston, the load is added at the HydroJunction (HydroID1669) located at the outflow point of Lake Houston (Figure 5.4.1b).

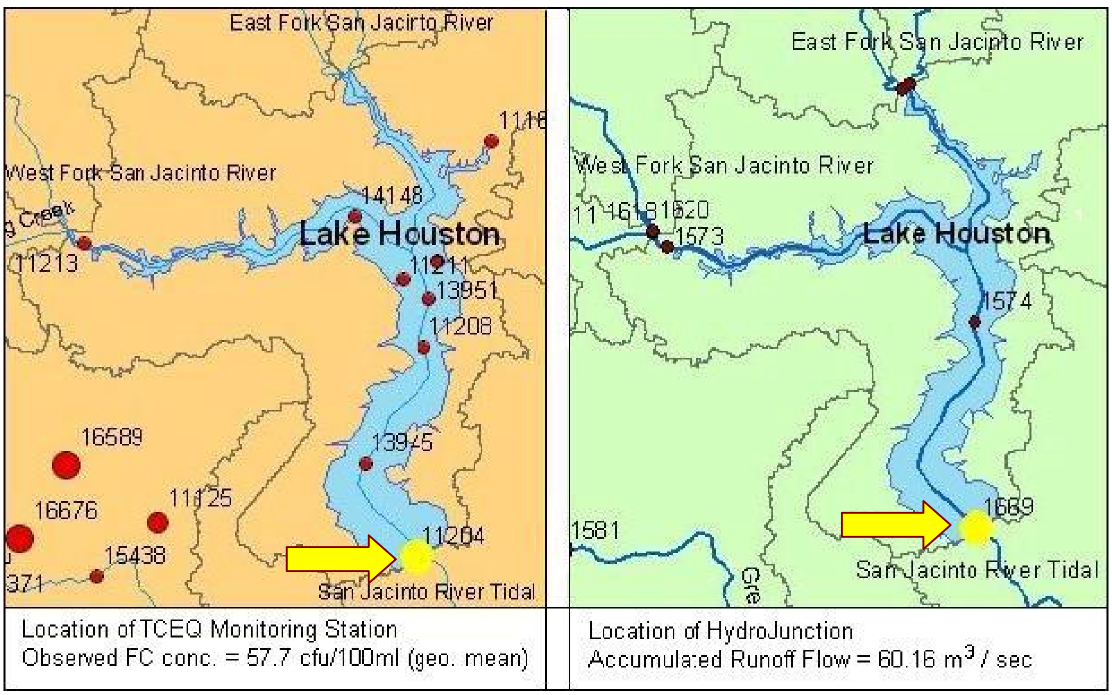


Figure 5.4.1: a) TCEQ monitoring station; and b) HydroJunction located at the discharge point of Lake Houston

Mean runoff flow accumulated at the HydroJunction located at the discharge point of Lake Houston (Figure 5.4.1b) is 60.2 m^3 / sec (2124 ft^3 / sec). Geometric mean of observed fecal coliform concentration at TCEQ monitoring station number 11204, located 300 meter upstream from dam in Lake Houston (Figure 5.4.1a), is 57.7 cfu / 100 ml.

Load out of Lake Houston is computed as a product of the observed geometric mean of concentration and accumulated runoff flow.

Load from Lake Houston = Flow × Concentration

$= 60.16\ m^3 / sec \times 57.67\ cfu / 100\ ml \times 106\ ml / m^3$

$= 3.47 \times 107\ cfu / sec \times 365\ days / year \times 86400\ sec / day$

$= 1.09 \times 1015\ cfu / year$

This load is then decayed through San Jacinto River and Houston Ship Channel for the distance of the Lake Houston discharge point to the Upper Galveston Bay, a distance of 47 km, with a first order decay rate of 1.5 day^{-1}.

5.4.2 FECAL COLIFORM LOAD FROM LAKE LIVINGSTON

Fecal coliform load flowing out of Lake Livingston is added at the HydroJunction (HydroID 1677) located at the outflow point of Lake Livingston (Figure 5.4.2).

Mean annual discharge from Lake Livingston is estimated from USGS stream flow data recorded at USGS gaging station at Trinity River near Goodrich, TX (site number 08066250). The gaging station is located roughly 16 km downstream from Lake Livingston and has mean annual stream flow records for 35 years from 1966 to 2000. Average of the thirty-five years mean annual flow data is computed to be 228.2 m^3 / sec (8058.9 ft3 / sec).

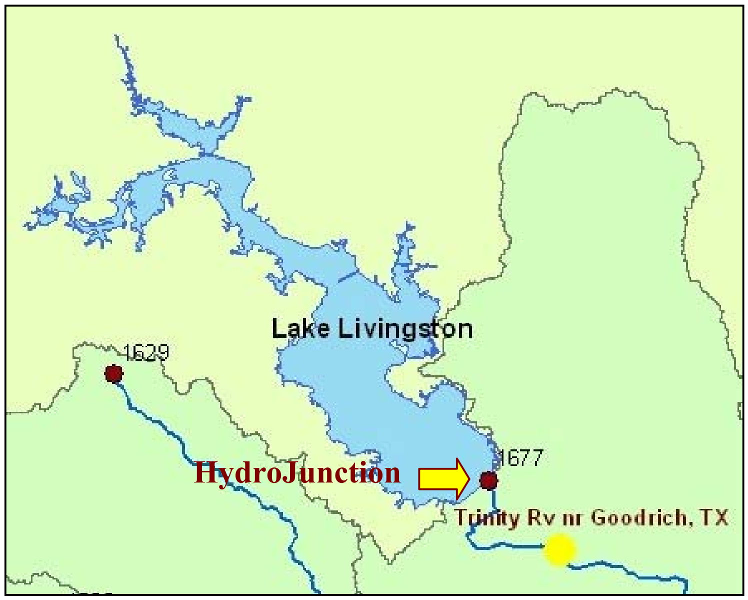


Figure 5.4.2: HydroJunction located at the discharge point of Lake Livingston

Geometric mean of observed fecal coliform concentration at TCEQ monitoring station number 10898, located at Trinity River at the Lake Livingston discharge below dam (Figure 5.4.3), is 20.9 cfu / 100 ml.

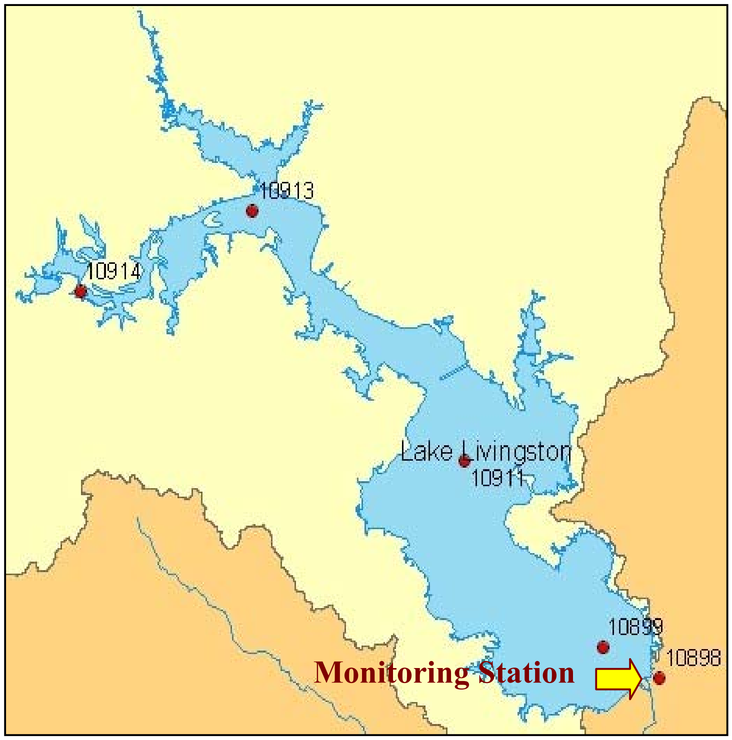


Figure 5.4.3: TCEQ Monitoring Station (10896) located at the discharge point of Lake Livingston

Fecal coliform load from Lake Livingston is computed as a product of discharge from Lake Livingston and observed fecal coliform concentration at the discharge point.

Load from Lake Livingston = Flow × Concentration

= 228.2 m^3 / sec × 20.9 cfu / 100 ml × 106 ml / m^3

= 4.78 × 107 cfu / sec × 365 days / year × 86400 sec /day

= 1.51 × 1015 cfu / year

This load is then decayed through Trinity River for the distance of the Lake Livingston discharge point to Trinity Bay, a distance of 192.5 km.

5.4.3 RESULT

Estimated loadings of fecal coliform from Lake Houston and Lake Livingston is presented in Table 5.3.1.

Table 5.4.1: Decayed Fecal Coliform Load from Lake Houston and Lake Livingston

Lake	Mean Annual Flow (m^3/sec)	Geometric Mean of Observed FC Conc. (cfu/100ml)	Load (cfu/year)	Downstream Length (km)	Stream Velocity (m/sec)	Decayed Lake Load (cfu/yr)	Percent Decay
Lake Houston	60.2	57.7	1.1E+15	47.0	0.53	2.4E+14	78%
Lake Livingston	228.2	20.9	1.5E+15	192.5	2.62	4.2E+14	72%

5.5 Fecal Coliform Contribution from Other Sources

Some other sources of fecal coliform contamination in the bay are from waste water treatment plant bypasses, failing septic systems, sludge application fields and boat traffic.

5.5.1 Fecal Coliform Load from WasteWater Treatment Plant Bypasses and Septic System

Estimation of fecal coliform contribution from waste water treatment plant bypasses and failing septic system in previous studies found insignificant contribution (Jensen and Su 1992, Guillen et al. 1994). Loading from bypasses is estimated to be 1.44×10^{14} cfu/year and failing septic systems is 2.7×10^{10} cfu/year (Guillen et. al. 1994).

5.5.2 Fecal Coliform Load from Boat Traffic

Elevated fecal coliform concentrations observed along the Houston Ship Channel may indicate fecal coliform contributions from boat traffic (Figure 4.1.1 & 4.1.2). Estimation of fecal coliform load from boat traffic is not possible due to limited available data.

However, information available for Clear Lake area through personal communication with Alan Hunter at Maritime Sanitation suggested signification contribution of fecal coliform from boat traffic. There are approximately 10,000 boats in the Clear Lake area. Approximately 1% of these boats use free pumping facility available from Maritime Sanitation. The maritime sanitation pumping station pumps approximately 2300 to 2500 gallons of waste per week. Waste pumped at the pumping stations goes to the municipal sewer system directly. There are several stations located around the lake which are private or available to public for a fee (Personal communication, Alan Hunter, Maritime Sanitation).

5.5.3 Location of Potential Fecal Coliform Contributors

Marinas, water quality permits, sludge application and inventoried sewage – all of this locations are potential contributors of fecal coliform load to Galveston Bay. A database containing the locations of marinas, water quality permits, sludge application and inventoried sewage was available from Texas Commission of Environmental Quality (TCEQ). Description and sources of these data records are presented below.

Marinas - 930 records

The original dataset used for the marina project came from a 1994 report "Texas Marina Facilities & Services Directory" by Dewayne Hollin with the Sea Grant College Program, Texas A&M University. This list consisted of marina names, addresses and a description of the facilites. Texas Commission on Environmental Quality (TCEQ) staff then digitized the locations. Additional marinas were added to the database by searching state park maps, river authority maps, USCOE lake maps and USGS topographic maps.

Sludge Application Sites - 192 records

Land application of sludge locations were supplied by the Texas Pollutant Discharge Elimination System (TPDES) at Texas Commission on Environmental Quality (TCEQ). The locations were digitized using maps provided during the application process.

Water Quality Permits - 5,848 records

Locations for water quality permits were obtained from the Water Quality Division of Texas Commission on Environmental Quality (TCEQ).

Inventoried sites - 32.357 records

Additional potential sources of contamination have been recorded by field work pertaining to the Source Water Assessment and Protection Program; formerly know as the Wellhead Protection Program, at TCEQ. Various sites were recorded through field work by Texas Commission on Environmental Quality staff, Texas Rural Water Association staff and local volunteers. Collection methods included GPS, map digitizing and county tax assessor data (Personal communication, Sean Ables, GIS Specialist, Source Water Assessment & Protection Program, Texas Commission on Environmental Quality, April 2003).

The locations of the marinas, water quality permits, sludge application and inventoried sewage are presented in Figure 5.5.1.

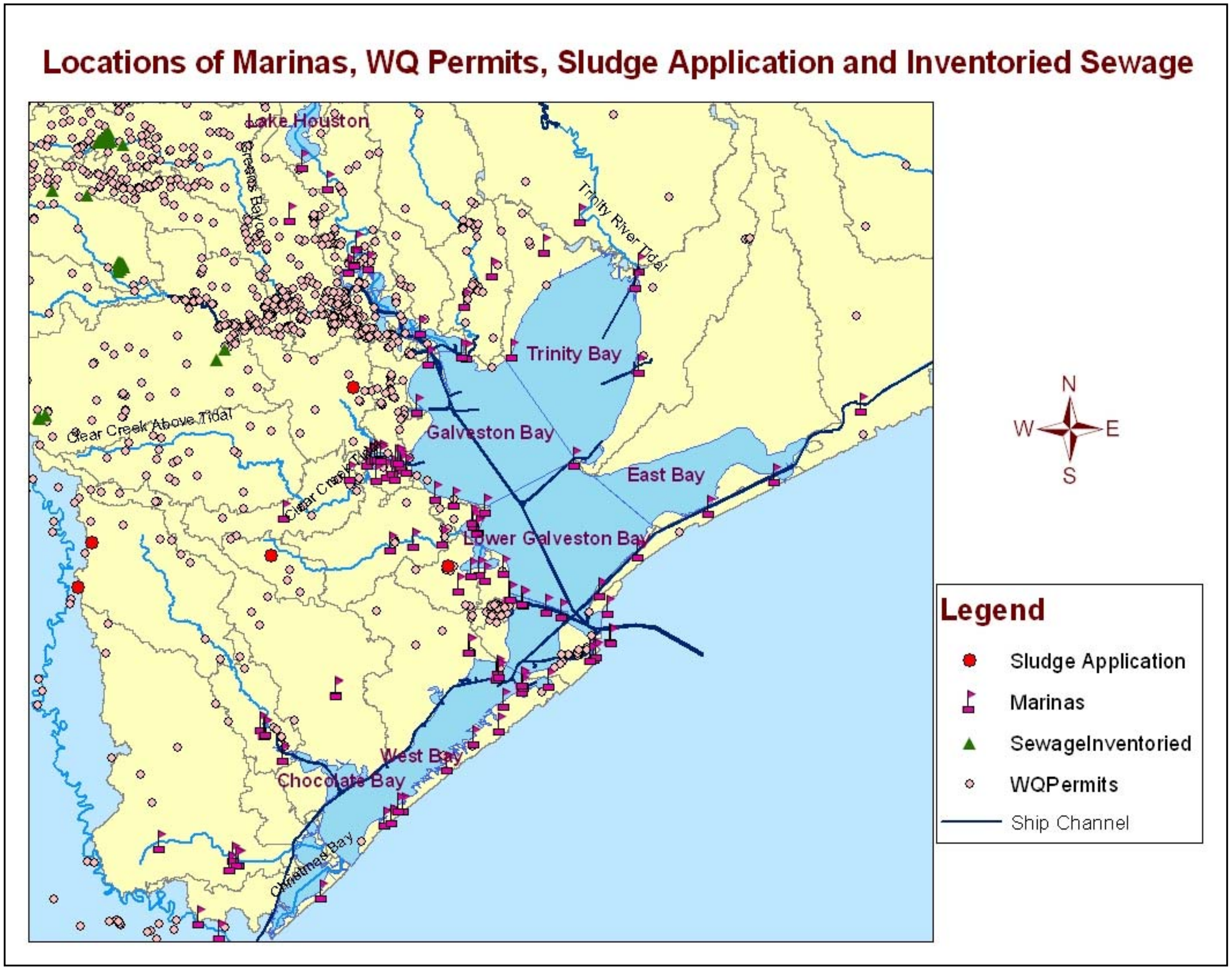


Figure 5.5.1: Locations of the potential fecal coliform contributors

5.6 Estimation of Avian Load

5.6.1 METHODOLOGY

The four important variables in estimating fecal coliform loads from bird sources are average number of birds at a particular location, amount of excretion per bird, concentration of fecal coliform in excretion for a specific species type and finally approximate percentage of load reaching the bay

The first step in the process of estimating fecal coliform loadings from bird is to identify species of birds residing in and around the bay, their population and their location. This is done by examining data from U.S. Fish and Wildlife Service Texas Colonial Waterbird Surveys from 1973 to 2001.

This analysis and literature indicates Laughing Gulls to be the most common species in Galveston Bay. This study attempts to estimate approximate loadings of fecal coliform from this single species in Galveston Bay. Amount of excretion per bird and concentration of fecal colifom in droppings of the Laughing Gull is estimated by reviewing available literature. Percent of load reaching the bay is approximated from the duration of time a bird spends on water based on best professional judgment (Personal communication, Dr. Barbara Moore, UT San Antonio and Dr. Martin Underwood, US Fish and Wildlife Services, February 2003).

5.6.2 PROCEDURE OF APPLICATION

5.6.2.1 Bird Data

Data from U.S. Fish and Wildlife Service Texas Colonial Water-bird Surveys from 1973 to 2002 is used to estimate fecal coliform loading from avian sources in the study area. [This dataset is made available to Dr. Barbara Moore, University of Texas at San Antonio, by Mr. Martin K. Underwood, US Fish and Wildlife Service with input from Dr. Robert McFarlane, McFarlane and Associates, Houston, Texas.] Texas Colonial Water-bird surveys are conducted annually by volunteers. The surveys attempt to count nesting bird pairs in colonies along the Texas coast.

The average counts are calculated using the available bird counts of breeding pairs available over the years of 1973 to 2002 for each location. Table 5.6.1 shows the average number of breeding pairs, number of locations of colonies and bird counts for each species computed from the database. It is observed that the species ‘Laughing Gull’ is the most abundant bird species. Colonies of breeding pairs of this particular species are located at 43 locations in the impaired segments.

Table 5.6.1: Summary of Bird Data

	Species	Average Breeding Pair Count	Number of Locations	Sum Of Count
1	Laughing Gull	31623	43	405
2	Royal Tern	14311	20	79
3	Sandwich Tern	7494	15	57
4	Black Skimmer	7487	63	368
5	Cattle Egret	5902	22	187
6	Forster's Tern	4963	52	446
7	White Ibis	4031	26	134
8	Tricolored Heron	3162	41	350
9	Least Tern	3049	57	207
10	Roseate Spoonbill	2155	26	197
11	Snowy Egret	2146	36	276
12	Great Egret	1890	32	258
13	Neotropic Cormorant	1429	16	137
14	Gull-billed Tern	1236	37	112
15	White-faced Ibis	859	10	91
16	Caspian Tern	791	15	59
17	Black-crowned Night-Heron	783	22	182
18	Great Blue Heron	632	33	247
19	Brown Pelican	544	6	26
20	Little Blue Heron	253	17	82
21	Double-crested Cormorant	125	1	1
22	Reddish Egret	110	21	134
23	Yellow-crowned Night-Heron	45	7	16
24	Anhinga	39	4	7
25	American Oystercatcher	32	19	61
26	Green Heron	10	2	5
27	Fulvous Whistling Duck	4	1	2

A map showing the location of all bird colonies is prepared and presented in Figure 5.6.1. Visual inspection of the map of shows significant correlation of the location of bird colonies and elevated level of fecal coliform concentration within West Bay (Figure 4.1.1, Figure 4.2.2 and Figure 5.6.1).

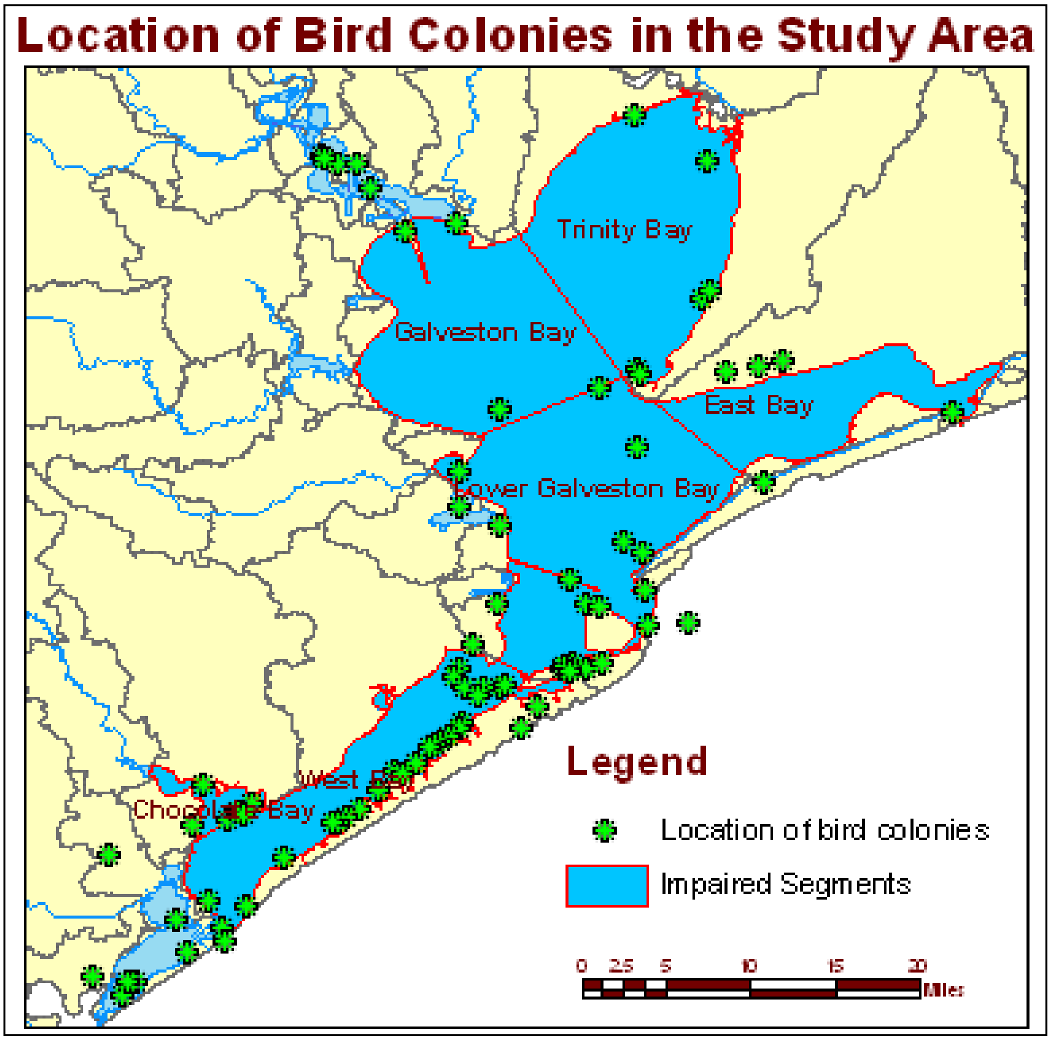


Figure 5.6.1: Location of Colonies of Breeding Pairs of Birds

5.6.2.2 Fecal Coliform in Gull Droppings

Information on the concentration of fecal coliform in bird droppings and the amount of daily excretion is limited. Published levels of fecal coliform concentration in different species of gulls found in literature are presented in Table 5.6.2.

Table 5.6.2: Fecal Coliform Concentration in Gull species

Species	Location of Study	Concentration (CFU/gm)	References
Ring -billed gull	NY, USA	3.70E+08	Alderisio & DeLuca, 1999
Ring -billed gull	Canada	5.20E+06	Levesque et al., 1993
Ring -billed gull	Canada	2.10E+08	Levesque et al., 2000
Herring gull (captive)	England	5.20E+08	Gould & Fletcher, 1978
Common gull (captive)	England	6.20E+08	Gould & Fletcher, 1978
Black-headed gull (captive)	England	3.02E+08	Gould & Fletcher, 1978

Based on data collected by Portnoy (1990), Herring gulls [*Larus argentatus*] had a mean defecation frequency of 3.1 (+/- 1.0)/hour with a mean defecation mass of 0.53 gm (+/- 0.09) for a 24 hr dry weight excretion total of 39.4 gm/bird. As cited by Portney, this value was over twice the 17.1 gm/bird observed for caged gulls by Nixon & Oviatt (1973).

In a separate paper from France, Marion et al. (1994), citing a 1971 paper by Spann, estimate that herring gulls excrete 15 gm/bird dry weight. The authors (Marion et al. 1994) estimated that 4 gm out of 15 gm/bird excretion entered the lake in their study.

5.6.2.3 Estimation of loadings from Laughing Gull

Average number (arithmetic mean) of breeding pairs of Laughing Gull at each location is computed from the available data. A location map showing the number of breeding pairs of Laughing Gulls at each location using graduated symbols is presented in Figure 5.6.2.

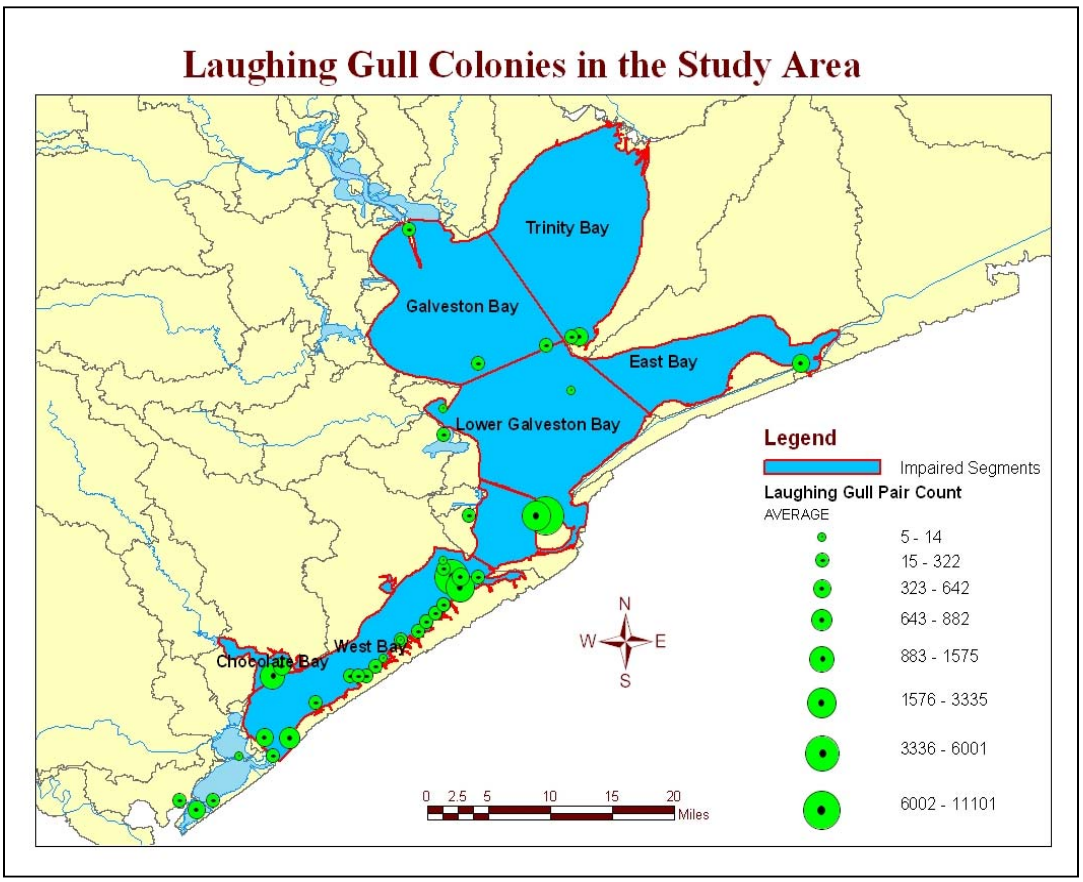


Figure 5.6.2: Laughing Gull colonies in the study area

A limitation in the number of average breeding pair count that is used in this study for loading estimation is that it fails to include the number of birds that are not breeding pairs (Personal communication, Dr. Robert McFarlane, McFarlane and Associates).

The loading is computed at each location as:

Load from Gull = Number of breeding pairs × 2 × Amount of excretion per bird × FC concentration in bird dropping × percent of FC reaching the bay (5.3.1)

An important point for the Galveston Bay study is that the adult laughing gull is much smaller [15 - 17 inches] than the adult herring gull [23 – 26 inches] for which published fecal coliform values are available. Therefore, an approximate amount of 25gm/ bird is reasonable as the amount of excretion per bird based on ratio of body (Personal communication, Dr. Moore, Professor, UT San Antonio February 2003). Based on published data documented in the previous section of this report, an estimated fecal coliform concentration of 10^8 cfu/gm of gull dropping is used for the estimation.

Laughing Gulls spend time on water only during the daylight hours. However, they may roost near or over water. The amount of time they spent on water during daylight hours is highly variable in different seasons. A 25% to 50% contribution of fecal coliform to bay water is a reasonable approximation. This is also in conformation with literature data where the authors estimated that 4 gm out of 15 gm/bird entered the lake they were studying (Personal communication, Dr. Moore, Professor, UT San Antonio February 2003).

For this study, an estimation of 50% of the fecal coliform reaching the water was used. While this is a conservative approach, it may compensate for the loadings from individual, non-breeding Laughing Gulls that are not are not included in bird count.

5.6.3 RESULT

Estimation of loadings from Laughing Gull is shown in Table5.6.3.

Table 5.6.3: Fecal Coliform Load from 'Laughing Gull'

Bay Segment	Load from Laughing Gull (cfu/yr)
Upper Galveston Bay (2421)	2.88E+14
Trinity Bay (2422)	3.62E+14
East Bay (2423)	3.07E+14
West Bay (2424)	1.23E+16
Chocolate Bay (2432)	1.90E+15
Lower Galveston Bay (2439)	1.32E+16

5.7 Estimation of Total Loadings

Total loading is computed as a sum of non-point loadings – adjacent and upstream, point sources loadings and avian load. Point sources loadings are available from permit data compiled by a previous Galveston Bay Estuary Program Project (Armstrong and Ward 1993). Table 5.7.1 summarizes the total loading estimation to impaired segments.

Table 5.7.1: Summary of Estimated Loadings to the Impaired Segments

	Adjacent Non-Point Load (cfu/yr)	Upstream Non-Point Load (cfu/yr)	Load from Lake (cfu/yr)	Point Source Load (cfu/yr)	Load from Laughing Gull (cfu/yr)	Total Load (cfu/yr)
Upper Galveston Bay (2421)	1.55E+15	3.18E+16	2.36E+14	1.73E+13	2.88E+14	**3.38E+16**
Trinity Bay (2422)	3.77E+15	1.48E+16	4.21E+14	1.47E+12	3.62E+14	**1.94E+16**
East Bay (2423)	2.52E+15	3.72E+15		0.00E+00	3.07E+14	**6.55E+15**
West Bay (2424)	3.30E+15	4.71E+15		1.54E+13	1.23E+16	**2.03E+16**
Chocolate Bay (2432)	3.91E+15	1.67E+15		7.46E+12	1.90E+15	**7.49E+15**
Lower Galveston Bay (2439)	2.03E+15	3.79E+15		2.63E+13	1.32E+16	**1.90E+16**
Total	**1.71E+16**	**6.05E+16**	**6.57E+14**	**6.80E+13**	**2.83E+16**	**1.07E+17**
Percentage	**16.0%**	**56.7%**	**0.6%**	**0.1%**	**26.6%**	**100.0%**

5.8 Continuous Stirred Tank Reactor (CSTR) Modeling

5.8.1 METHODOLOGY

A simple Continuous Stirred Tank Reactor (CSTR) model is applied to the six impaired segments of Galveston Bay. A Continuous Stirred Tank Reactor (CSTR) model treats each segment of the bay as a closed system. The model, as the name implies, assumes complete mixing of the waste load in the entire body of water and steady state condition as the "start-up" of the process was sufficiently far removed in the past. The equation used for a Continuous Stirred Tank Reactor (CSTR) model is:

$$Concentration, c = \frac{W}{Q + K_B V}$$

Where, W is pollutant load, Q is runoff volume, K_B is the overall net first order decay rate and V is the volume of water body.

The Continuous Stirred Tank Reactor (CSTR) model does not allow for dispersion within the bay segments, hydrodynamic mixing and tidal mixing. However, it accounts for deactivation rate of fecal coliform, the most significant controlling parameter for fecal coliform concentration in the Galveston Bay. This model is used to verify the magnitude of computed loading.

5.8.2 PROCEDURE OF APPLICATION

5.8.2.1 Computation of Volumes of the six Impaired Segments in the Study Area:

Volumes of the impaired segments are calculated from as a product of mean depth and area of each bay segment. Mean depth of each bay segment is computed from bathymetry data as described in Chapter 3 of this report. Volumes computed from bathymetry data are shown in Table 5.8.1.

Table 5.8.1: Volumes of the six segments in Galveston Bay:

Impaired Segment	Area (km^2)	Mean Depth (m)	Volume (m^3)
Upper Galveston Bay (2421)	299.1	2.56	7.65E+08
Trinity Bay (2422)	317.5	2.11	6.70E+08
East Bay (2423)	148.9	1.52	2.23E+08
West Bay (2424)	195.4	2.04	3.99E+08
Chocolate Bay (2432)	21.1	1.95	4.10E+07
Lower Galveston Bay (2439)	362.4	2.61	9.47E+08

5.8.2.2 Estimation of Total Flow

Estimation of total inflow into the six impaired segments of Galveston Bay included in this study is computed as a sum of effluent flow, non-point runoff from adjacent watershed and non-point runoff from upstream watershed. The source of effluent flow data is the point-source characterization study in Galveston Bay (Armstrong and Ward 1993). Table 5.8.2 presents the estimated total inflow to the Galveston Bay.

Table 5.8.2: Total Inflow to the Impaired Segments (Trinity River flow adjusted)

	Effluent Flow (m^3/yr)	Runoff from Adjacent Watershed (m^3/yr)	Runoff from Upstream Watershed (m^3/yr)	Total Flow (m^3/yr)
Upper Galveston Bay (2421)	1.65E+09	1.11E+08	3.10E+09	4.87E+09
Trinity Bay (2422)	1.58E+09	2.47E+08	6.96E+09	8.79E+09
East Bay (2423)	0.00E+00	2.02E+08	4.74E+08	6.76E+08
West Bay (2424)	7.72E+06	1.35E+08	2.62E+08	4.05E+08
Chocolate Bay (2432)	3.73E+06	1.40E+08	1.25E+08	2.69E+08
Lower Galveston Bay (2439)	1.31E+08	1.20E+08	1.06E+08	3.57E+08

There is one adjustment made to the estimated runoff flow. It was found that the stream flow in the Trinity River is significantly higher than the estimated runoff flow. The discrepancy is reasonable considering the fact that the Trinity River receives flow from upstream and Lake Livingston. The estimated runoff value accounts for only surrounding watersheds not the upstream flow. To adjust for this limitation, the inflow into Trinity Bay from upstream watersheds through Trinity River is replaced with mean annual flow value at USGS stream gauge (site number 8066500) located on Trinity River at Roymayor, Texas, which is 6.96×10^9 m3/year.

5.8.2.3 Fecal Coliform Decay Rate in Impaired Segments

The following values (Table 5.8.3) for fecal coliform decay rates applicable to estuarine environments are available from published literature (Bordalo et al. 2002). Temperature range for this data is from 28.6 to 33.8^{0}C. Salinity ranges in these data is shown in Practical Salinity Unit (PSU) or parts per thousand.

Table 5.8.3: Fecal Coliform Die-Off Rates

	Average T_{90} (hr)	T_{90} (day)	K_B (day^{-1})
Low Salinity (0.8 psu)	37.1 ± 2.9	1.7 – 1.4	1.4 – 1.6
Progressive Mix (14.2 psu)	27.4 ± 2.5	1.2 – 1.0	1.8 – 2.2
Rapid Mix (25.2 psu)	14.5 ± 0.8	0.64 – 0.57	3.6 – 4.0

Based on the relative salinity in the Galveston Bay segments and literature values on fecal coliform decay rate, T_{90} values of 1.0 to 1.2 are assigned to the bay segments with decreasing salinity.

5.8.3 Result

Once all the parameters are computed, a simple Continuous Stirred Tank Reactor (CSTR) model accounting for estimated total loadings and fecal coliform decay is applied to all of the six impaired segments. Model parameters and expected fecal coliform concentration computed from Continuous Stirred Tank Reactor (CSTR) model for each of the impaired bay segments is presented in Table 5.8.4.

Table 5.8.4: Continuous Stirred Tank Reactor (CSTR) Model Parameters, Inputs and Outputs

	Volume of Bay Segment (m^3)	Total Flow (m^3/yr)	Total Load (cfu/yr)	T_{90} (day)	First Order Decay, K_B (day^{-1})	Concentration (colonies/m^3)	Concentration (cfu/100ml)
Upper Galveston Bay (2421)	7.65E+08	**4.87E+09**	**3.38E+16**	1.2	1.9	6.27E+04	**6.3**
Trinity Bay (2422)	6.70E+08	**8.79E+09**	**1.94E+16**	1.2	1.9	4.06E+04	**4.1**
East Bay (2423)	2.23E+08	**6.76E+08**	**6.55E+15**	1.1	2.1	3.83E+04	**3.8**
West Bay (2424)	3.99E+08	**4.05E+08**	**2.03E+16**	1.0	2.3	6.05E+04	**6.0**
Chocolate Bay (2432)	4.10E+07	**2.69E+08**	**7.49E+15**	1.2	1.9	2.58E+05	**25.8**
Lower Galveston Bay (2439)	9.47E+08	**3.57E+08**	**1.90E+16**	1.0	2.3	2.39E+04	**2.4**

CHAPTER 6: RESULTS

6.1 Estimation of Loadings and Load Allocation

A total loading into six impaired segments of Galveston Bay is estimated to be 1.1×10^{17} cfu/year. Non-point loadings from upstream watersheds represent by far the maximum amount of loadings, 57% of total estimated loadings, into the Galveston Bay system which is 6.05×10^{16} cfu/year. The second and third largest loadings, accounting for 27% and 17% of total loadings respectively, are from gulls and non-point loadings from adjacent watershed segments. An estimated 2.83×10^{16} cfu/year of fecal coliform loading is from Laughing Gull population. Non-point source loading from adjacent watershed is an estimated 1.71×10^{16} cfu/year while point sources contribute considerably smaller amount of loading to the bay system, which 6.80×10^{13} cfu/year. Numeric values of loading estimation for each bay segment are presented in Table 5.7.1 in chapter 5. Figure 6.1.1 presents allocation of total loading into the four estimated categories of loadings.

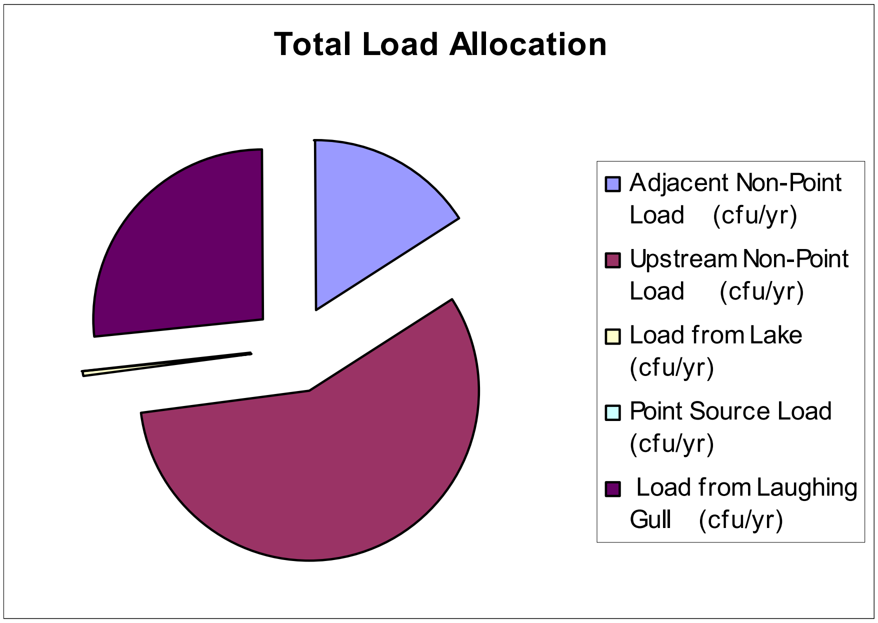


Figure 6.1.1: Allocation of total Load to Galveston Bay

Percent load allocation from different sources for each bay segment is presented in Table 6.1.1.

Table 6.1.1: Percent load allocation for each Bay Segment

	Adjacent Non-Point Load (cfu/yr)	Upstream Non-Point Load (cfu/yr)	Load from Lake (cfu/yr)	Point Source Load (cfu/yr)	Load from Laughing Gull (cfu/yr)	Total Load (cfu/yr)
Upper Galveston Bay (2421)	4.6%	93.8%	0.7%	0.1%	0.9%	100.0%
Trinity Bay (2422)	19.5%	76.5%	2.2%	0.0%	1.9%	100.0%
East Bay (2423)	38.5%	56.8%	0.0%	0.0%	4.7%	100.0%
West Bay (2424)	16.3%	23.2%	0.0%	0.1%	60.5%	100.0%
Chocolate Bay (2432)	52.2%	22.3%	0.0%	0.1%	25.4%	100.0%
Lower Galveston Bay (2439)	10.7%	19.9%	0.0%	0.1%	69.3%	100.0%
Percentage	**16.0%**	**56.7%**	**0.6%**	**0.1%**	**26.6%**	**100.0%**

Figure 6.1.2 and Figure 6.1.3 display relative loadings from various sources for the six impaired segments.

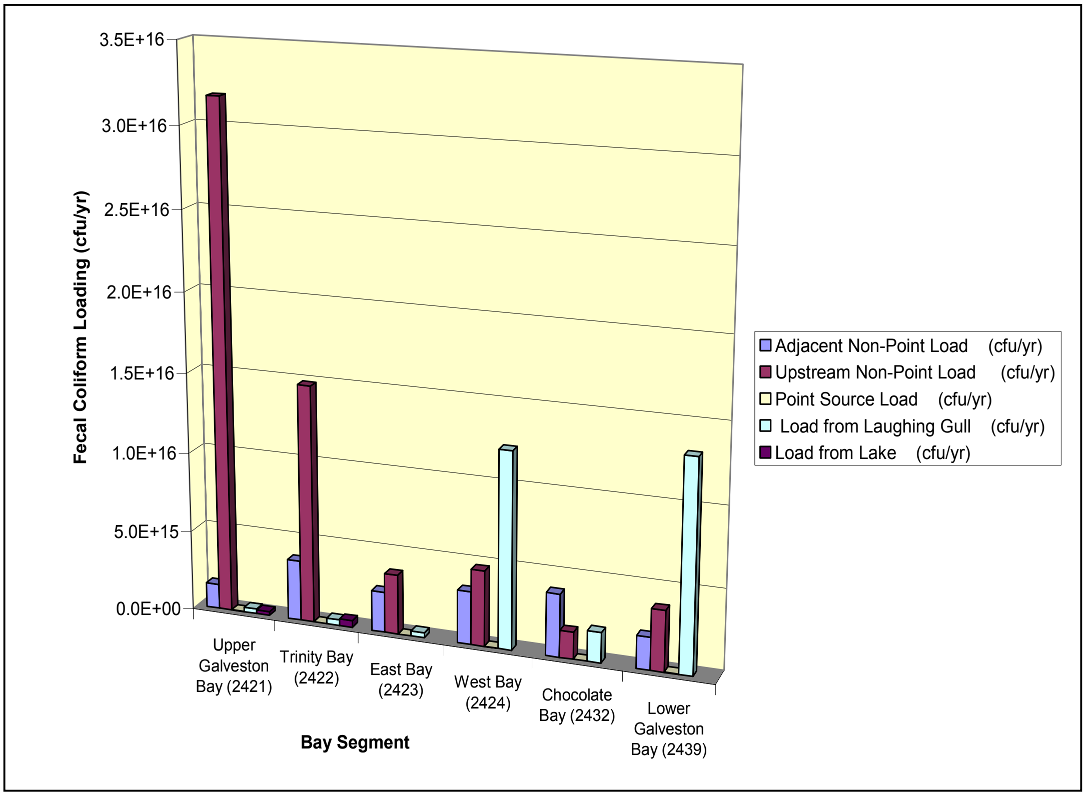


Figure 6.1.2: Load Allocation in the Impaired Bay Segments

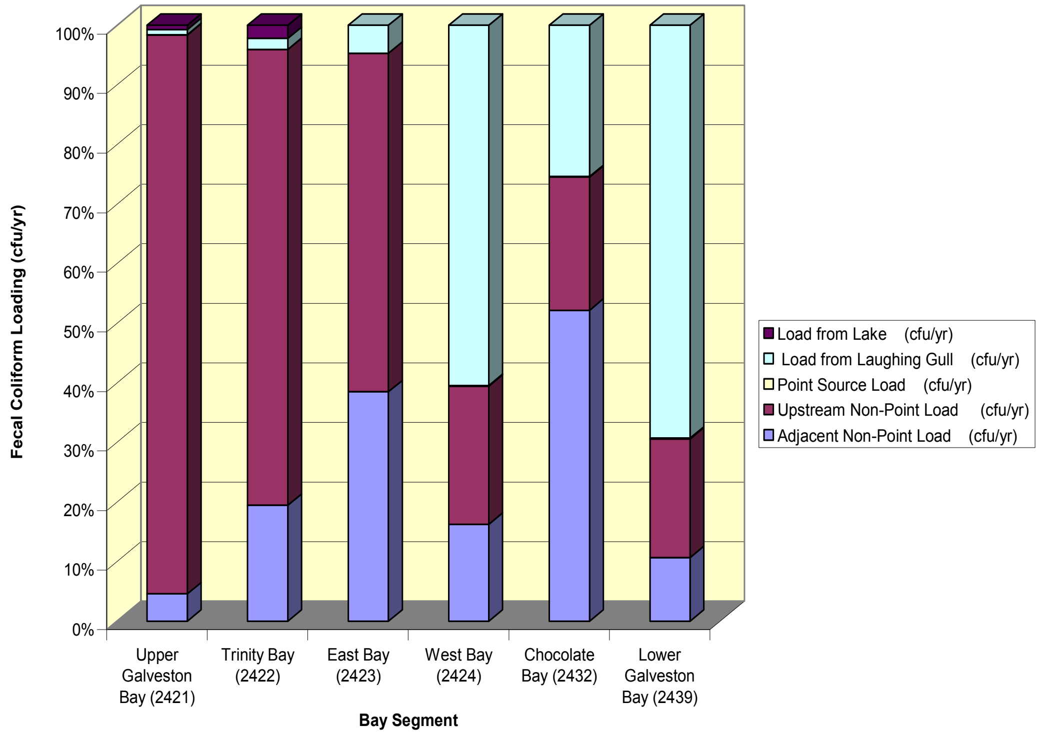


Figure 6.1.3: Percentage Load Allocation in the Impaired Bay Segments

Upper Galveston Bay receives approximately 94% of loadings from non-point loadings from upstream watersheds, most of which (67%) enters the bay through Houston Ship Channel. 19% of non-point loads from upstream watershed enters the Bay through Clear Lake, Clear Bayou Tidal and Armand Bayou Tidal. In Upper Galveston Bay, Houston Ship Channel (1006) and Houston Ship Channel/ Buffalo Bayou (1007) are the largest contributors of non-point fecal coliform loads from upstream watersheds.

Trinity Bay receives most of the loadings from non-point source. Approximately 20% of total loadings to Trinity Bay are from non-point loads generated from adjacent watershed and 77% are from upstream watershed segments that enter the bay through the Trinity River. Trinity bay is mostly bordered by grazing land and small communities. Trinity Bay also receives fecal coliform loadings from the Lake Livingston.

West Bay receives significant contributions (approximately 61%) of fecal coliform loadings from gull populations. Approximately 23% of total estimated fecal coliform loadings to West Bay are contributed from non-point loadings from upstream watersheds, which enter the bay through Bastrop Bay, Oyster Lake and Christmas Bay. Bastrop Bayou Tidal (1105) is the largest contributor of non-point fecal coliform loads from upstream watersheds. Approximately 16% of fecal coliform loadings in West Bay are non-point loadings from adjacent watershed.

East Bay receives most of its fecal coliform loadings (an estimated 95%) from non-point sources, the rest of loadings are from gull populations. East Bay does not receive any point sources input (Armstrong and Ward 1993). 38% of fecal coliform loadings in East Bay are non-point loadings from adjacent watershed. Approximately 57% of total estimated fecal coliform loadings to East Bay are contributed from non-point loadings from upstream watersheds, that enters the bay through Gulf Intracoastal Waterway. Significant amount of land use adjacent to East Bay comprises of wetlands. Previous studies (Jensen and Su 1992) suggested high level of fecal coliform inputs from the wetland area. The 1992 NPS study (Newell et al) used a value of 1600 col/100ml, the same as for barren land and lower than agricultural or open land. Jensen and Su study (1992) advises to use higher EMC value. The report also mentions that TDH personnel report that bay waters adjacent to wetland area shows rapid increases in fecal coliform levels following even moderate rain.

Computation in this study is made with an EMC value of 200 col/100ml for the wetland area. This value is based on the speculation that the wetlands act as repository for runoff from the upper area of the watershed. Much of the fecal coliform is contained within the wetland area and do not reach the bay (Personal communication, Dr. George ward, 2002). This speculation is supported by Mallin et al. (2001). Mallin et al. (2001) monitored levels of fecal coliform in tidal creek estuary systems along the North Carolina coast in New Hanover County. They suggested that bacterial abundance could be minimized through maximal use of natural or constructed wetlands for passive runoff treatment.

With lack of current data on fecal coliform concentration in wetland surrounding the East Bay, it is difficult to make any definitive decision on the EMC value used. Modeled concentration of fecal coliform in East Bay conforms to observed data supporting the speculation of retention of bacteria in East Bay. Monitoring effort in the wetland area is required to reach a valid conclusion regarding fecal coliform concentration in the wetlands surrounding East Bay.

Chocolate Bay is a relatively smaller bay segment. Unlike the other bay segments in this study, Chocolate Bay receives more non-point loadings from its adjacent watershed segment (52%) that the upstream segments (22%).Chocolate Bay receives approximately one fourth of its loadings from laughing gull population.

The most significant contribution of fecal coliform loadings to Lower Galveston Bay (approximately 69%) is from gull populations. Approximately 20% of total estimated fecal coliform loadings to Lower Galveston Bay are contributed from non-point loadings from upstream watersheds, 66% of which enter the bay through Dickinson Bayou. Dickinson Bayou Tidal (1103) is the largest contributor of non-point fecal coliform load from upstream watershed. Approximately 11% of fecal coliform loadings in Lower Galveston Bay are non-point loadings from adjacent watershed.

6.2 Modeling of Fecal Coliform Concentration

A simple Continuous Stirred Tank Reactor (CSTR) model accounting for estimated total loadings and fecal coliform decay in enclosed bay segments has given expected bay concentration of fecal coliform. Analysis of monitoring data presented in Chapter 4 of this report showed log-normal distribution of observed data. When data are log-normally distributed, the geometric mean is a direct measure in the *x* space of the mean of the data in the log space.

Geometric mean of $\{a_i\}_{i=1}^{n}$ is x_G.

$$x_G = \left[\prod_{i=1}^{n} x_i\right]^{\frac{1}{n}}$$

$$\therefore \log x_G = \frac{1}{n}\log\left[\prod_{i=1}^{n} x_i\right]$$

$$or \log x_G = \frac{1}{n}\sum_{i=1}^{n}\log x_i$$

$$or \log x_G = \overline{y}$$

Therefore, it is appropriate to compare the modeled concentration in this study to the geometric mean values of observed data. Expected fecal coliform concentration from model is presented with observed geometric mean values in the impaired segments in Table 6.3.1.

Table 6.4.1: Comparison of fecal coliform concentration from Continuous Stirred Tank Reactor (CSTR) modeling, TDH and TCEQ

	CSTR Concentration (cfu/100ml)	Geometric Mean of Observed Data (cfu/100ml)			
		TDH	% Difference	TCEQ	% Difference
Upper Galveston Bay (2421)	**6.3**	--	--	9.8	-36%
Trinity Bay (2422)	**4.1**	5	-18%	5.1	-20%
East Bay (2423)	**3.8**	3.8	0%	3.7	3%
West Bay (2424)	**6**	5.8	3%	5.9	2%
Chocolate Bay (2432)	**26**	--	--	--	--
Lower Galveston Bay (2439)	**2.4**	--	--	4.8	-50%

One of the objectives of the Continuous Stirred Tank Reactor (CSTR) modeling exercise was to examine if the loadings from different sources, which are estimated to be multiple magnitudes higher than observed concentration in the bay, are reasonable. The results from the Continuous Stirred Tank Reactor (CSTR) modeling show that the modeled concentration is in the same magnitude as the geometric mean concentration for Upper Galveston Bay, Trinity Bay, East Bay and West Bay and Lower Galveston Bay. Observed data is not available for Chocolate Bay. The decay rate of bacteria is found to be the most sensitive parameters in this simple modeling effort.

Modeled concentration in Upper Galveston Bay and Lower Galveston Bay are lower than observed concentration which indicates unaccounted loadings to the bay segments. Houston Ship Channel passes through these two bay segments, making them the major recipient of fecal coliform loadings from boat traffic that is not accounted for in the model.

Modeled concentration in Trinity Bay is also suggests unaccounted loadings. However, it is important to note the significant uncertainties involved with the modeling approach before making any direct association with percent differences of modeled concentration and observed concentrations to loadings to bay segments.

Modeled fecal coliform concentration in Chocolate Bay is much higher compared to the other bay segments. This may be artificially high due to relatively smaller volume of the bay segment a large adjacent watershed segment. Since Continuous Stirred Tank Reactor (CSTR) modeling does not account for hydrodynamic mixing and dispersion, the effect of concentration of one bay segment on another is also not represented.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This thesis presents an analysis of existing fecal coliform monitoring data from the period of 1995 to 2001 in six TCEQ Water Quality Segments in Galveston Bay, impaired for not meeting water quality standards for oyster water use. A GIS model is presented for estimation non-point fecal coliform loadings from adjacent and upstream watersheds. Loadings from upstream watersheds are decayed along the streams and channels entering the bay system in the model. A methodology for estimation of fecal coliform contribution from the Laughing Gull populations, the single most abundant bird species in Galveston Bay, in the bay is presented.

Estimation of total fecal coliform loading is made as a sum of loadings from point-sources of pollution, non-point sources of pollution from adjacent watersheds, non-point loadings from upstream watersheds, loadings from the Lake Houston and the Lake Livingston, and loadings from the Laughing Gull, most abundant bird species in the bay.

Extensive data analysis shows the proximity of cause - effect relationship for fecal coliform contamination. Impacts of bacterial contamination are felt close to their sources due to high decay rate of fecal coliform. Thus, the use of Continuous Stirred Tank Reactor (CSTR) model is plausible. An important point to note is that this model treats each of the segments as a self-contained waterbody and does not account for the hydrodynamic mixing and dispersion among the bay segments.

Data analysis also shows statistical consistency in observed data (log-normal distribution). This justifies the use of mean value for this study i.e., when the mean goes up, the spikes (maximum) in fecal coliform concentration also to goes up. Thus the mean values can be used in the future for determining the required reduction in fecal coliform loadings to meet water quality goals.

Point source loading data are taken from a previous characterization of point sources loadings from NPDES permit data (Armstrong and Ward 1993). Total point source loadings to Galveston Bay amount to 6.80×10^{13} cfu/year. Loadings from the watersheds are estimated as a product of runoff from the land surface and expected mean concentration of fecal coliform for a specific land use category. Estimation of non-point loadings from adjacent and upstream watersheds shows the relative effects of watersheds adjacent to the bay segments and the effect of upstream segments on the bay fecal coliform concentration. Non-point loading from upstream watersheds is the largest contributor of fecal coliform in the Galveston Bay system. An estimated 6.05×10^{16} colonies of fecal coliform bacteria enter the bay annually from non-point loadings generated from upstream watershed segments. Reduction of load in upstream segments will significantly lower the overall load in the bay segments. Total estimated non-point loading from adjacent watersheds is 1.71×10^{16} cfu/year.

Retention of non-point loadings in Lake Houston is considered while computing non-point loadings from upstream segments to Upper Galveston Bay. It is found that retention in Lake Houston (for residence time of 30.6 day) reduces fecal coliform load of 3.2×10^{15} cfu/yr to approximately 0. This result suggests that retention in upstream watershed segments will significantly lower loadings to Galveston Bay. Fecal coliform loads from Lake Houston and Lake Livingston are estimated and decayed to the bay segments. An estimated 2.36×10^{14} colonies of fecal colifrom bacteria leaving Lake Houston reaches the Upper Galveston Bay and 4.21×10^{14} colonies of fecal colifrom bacteria leaving Lake Livingston reaches the Trinity Bay annually.

It is inferred from literature data that fecal coliform loadings from waste water treatment plant bypasses and septic systems are not significant compared to loadings from non-point sources. Elevated fecal coliform concentration is observed along the Houston Ship Channel which may indicate fecal coliform contribution from boat traffic. Information gathered about boat traffic supports this speculation. However, estimation of fecal coliform loadings from boat traffic is not attempted due to limited available data.

Estimation of fecal coliform loading from Laughing Gull population is found as a product of average number of birds, amount of excretion per bird, fecal coliform concentration in bird dropping and percentage of fecal coliform reaching the bay. Total estimated fecal coliform loading from gull population is 2.83×10^{16} cfu/year. Loadings from Laughing Gull population show most significant contributions in West Bay and Lower Galveston Bay.

Fecal coliform concentrations obtained from simple Continuous Stirred Tank Reactor (CSTR) modeling is of the same magnitude as the geometric mean of observed concentration for Upper Galveston Bay, Trinity Bay, East Bay, West Bay and Lower Galveston Bay. The decay rate of bacteria is one of the most sensitive parameters in the simple modeling.

The expected concentration of fecal coliform from Continuous Stirred Tank Reactor (CSTR) modeling for Chocolate Bay is higher compared to those in other impaired segments. There are no observed data in this segment to compare the Continuous Stirred Tank Reactor (CSTR) concentration. However, fecal coliform loading from adjacent watershed segment for Chocolate Bay is likely to be artificially high.

The current study uses Texas Commission of Environmental Quality (TCEQ) stream segments for the stream network. With the current stream network, the adjacent watershed segments do not have any stream segments passing through them and, therefore, non-point runoff estimation does not account for decay in adjacent watershed segments. The adjacent watershed segment for Chocolate Bay is larger compared to the other bay segments resulting in high non-point loadings from the adjacent watershed.

This study serves as a basis for a framework of a regional bacterial model for TMDL study. The regional model can be adjusted for a general study to a very detailed TMDL study. An example case is Chocolate Bay. Fecal coliform load generated from adjacent watershed area for Trinity Bay is not decayed due to the absence of stream segment in the adjacent watershed and, therefore, the entire load enters the Trinity Bay. However, National Hydrography Network (NHD) shows smaller streams and channels located in this adjacent watershed (Figure 7.1.1).

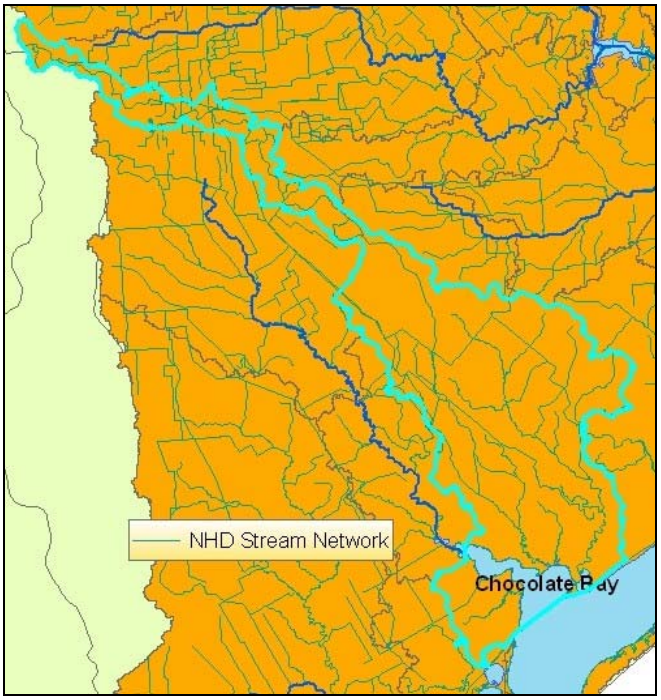


Figure 7.1.1: NHD Network in the Watershed Segment adjacent to Trinity Bay

Replacing the current Texas Commission of Environmental Quality (TCEQ) stream network with the more detailed National Hydrography Network (NHD) network will reduce non-point fecal coliform loadings into the Trinity Bay due to decay in channels.

7.2 Recommendations

1. Galveston Bay is a complex bay system with several streams and tributaries draining to it and multiple outlets to the Gulf of Mexico. It is important to develop a refined model (Finite Segment Model) on the bay segments to determine maximum allowable loadings to the Bay.

2. The model could be calibrated with salinity data. However, it is important to establish a decay rate for this region. The values found in the literature are too widely varied to scientifically pick a single value.

3. The model for laughing gull loadings can be used for estimating the loadings from other species of birds.

4. Fecal coliform sampling is required in the Chocolate Bay area.

5. Fecal coliform sampling is required in the wetland area surrounding East Bay.

6. Parameters affecting die-off rate of bacteria in water are manifold and exhibit complex relationships. Therefore, determination of site specific die-off rates of fecal coliform for Galveston Bay is required for appropriate modeling.

7. Boat traffic contributes significant fecal coliform loadings to Galveston Bay. Measure should be taken to better quantify loadings from this source and control loadings from this source as it is readily controllable.

Appendix A: Anderson Land Use Code

Classification Codes-first and second level categories:

1 Urban or Built-Up Land

- 11 Residential
- 12 Commercial Services
- 13 Industrial
- 14 Transportation, Communications
- 15 Industrial and Commercial
- 16 Mixed Urban or Built-Up Land
- 17 Other Urban or Built-Up Land

2 Agricultural Land

- 21 Cropland and Pasture
- 22 Orchards, Groves, Vineyards, Nurseries
- 23 Confined Feeding Operations
- 24 Other Agricultural Land

3 Rangeland

- 31 Herbaceous Rangeland
- 32 Shrub and Brush Rangeland
- 33 Mixed Rangeland

4 Forest Land

- 41 Deciduous Forest Land
- 42 Evergreen Forest Land
- 43 Mixed Forest Land

5 Water

- 51 Streams and Canals
- 52 Lakes
- 53 Reservoirs

54 Bays and Estuaries

6 Wetland

61 Forested Wetlands

62 Nonforested Wetlands

7 Barren Land

71 Dry Salt Flats

72 Beaches

73 Sandy Areas Other than Beaches

74 Bare Exposed Rock

75 Strip Mines, Quarries, and Gravel Pits

76 Transitional Areas

77 Mixed Barren Land

8 Tundra

81 Shrub and Brush Tundra

82 Herbaceous Tundra

83 Bare Ground

84 Wet Tundra

85 Mixed Tundra

9 Perennial Snow and Ice

91 Perennial Snowfields

92 Glaciers

Appendix B: Salinity Data in Galveston Bay

Table B.1: Statistics of salinity data (parts per thousand) at monitoring stations located in Galveston Bay segments

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
1	2421	Upper Galveston Bay	13303	1.1	29.7	16.3	677
2	2421	Upper Galveston Bay	13304	1.0	24.2	16.0	54
3	2421	Upper Galveston Bay	13305	1.8	25.0	13.9	203
4	2421	Upper Galveston Bay	13306	1.0	25.6	12.5	133
5	2421	Upper Galveston Bay	13307	1.7	28.3	17.5	318
6	2421	Upper Galveston Bay	13312	0.6	27.1	15.4	408
7	2421	Upper Galveston Bay	14554	0.0	28.8	9.8	171
8	2421	Upper Galveston Bay	14555	1.0	26.8	11.0	139
9	2421	Upper Galveston Bay	14556	1.0	24.0	10.2	123
10	2421	Upper Galveston Bay	14557	0.1	27.9	9.1	221
11	2421	Upper Galveston Bay	14560	0.6	28.6	11.7	258
12	2421	Upper Galveston Bay	14561	0.7	24.1	11.3	204
13	2421	Upper Galveston Bay	14562	0.5	24.8	11.7	211
14	2421	Upper Galveston Bay	14563	0.0	26.9	8.5	277
15	2421	Upper Galveston Bay	14565	0.8	24.5	11.3	212
16	2421	Upper Galveston Bay	14566	1.4	27.1	12.5	326
17	2421	Upper Galveston Bay	14569	1.1	28.1	12.5	315
18	2421	Upper Galveston Bay	14570	0.7	27.1	11.6	282
19	2421	Upper Galveston Bay	14571	0.6	27.0	11.2	263
20	2421	Upper Galveston Bay	14572	1.0	25.0	11.0	222
21	2421	Upper Galveston Bay	14579	1.0	25.5	11.4	117
22	2421	Upper Galveston Bay	14580	1.0	26.7	10.6	117
23	2421	Upper Galveston Bay	14581	1.0	29.1	12.1	288
24	2421	Upper Galveston Bay	14582	1.0	29.8	12.1	321
25	2421	Upper Galveston Bay	14598	0.3	24.0	10.0	244
26	2421	Upper Galveston Bay	15242	0.2	26.0	10.0	21
27	2421	Upper Galveston Bay	15243	4.9	20.0	13.7	24
28	2421	Upper Galveston Bay	15244	1.9	20.5	11.7	17
29	2421	Upper Galveston Bay	15245	3.0	22.5	12.0	24
30	2421	Upper Galveston Bay	15246	5.1	19.8	13.7	24
31	2421	Upper Galveston Bay	15247	4.6	19.8	11.9	17
32	2421	Upper Galveston Bay	15903	1.6	17.1	10.1	24
33	2421	Upper Galveston Bay	15904	3.5	18.1	10.7	27

	Segment Number		StationID	Minimun	Maximun	Average	Count
34	2421	Upper Galveston Bay	15906	1.3	18.5	12.0	24
35	2421	Upper Galveston Bay	15907	7.2	19.9	12.2	15
36	2421	Upper Galveston Bay	15908	7.2	19.6	12.5	21
37	2421	Upper Galveston Bay	15909	2.5	19.3	13.0	21
38	2421	Upper Galveston Bay	15910	10.0	21.0	14.5	18
39	2421	Upper Galveston Bay	15911	0.8	19.9	10.1	17
40	2421	Upper Galveston Bay	15913	6.6	18.8	12.0	15
41	2421	Upper Galveston Bay	16201	2.5	10.1	6.6	10
42	2421	Upper Galveston Bay	16203	1.9	9.5	6.6	11
43	2421	Upper Galveston Bay	16207	1.0	14.7	8.4	14
44	2421	Upper Galveston Bay	16208	2.6	15.5	8.9	14
45	2421	Upper Galveston Bay	16209	3.1	18.4	10.4	13
46	2421	Upper Galveston Bay	16213	2.7	15.5	9.5	14
47	2421	Upper Galveston Bay	16215	2.0	18.2	8.0	14
48	2421	Upper Galveston Bay	16230	1.8	12.3	7.0	14
49	2421	Upper Galveston Bay	16503	14.9	21.8	18.9	5
50	2421	Upper Galveston Bay	16507	14.8	23.3	19.2	7
51	2421	Upper Galveston Bay	16510	13.1	24.4	19.3	11
52	2421	Upper Galveston Bay	16511	18.9	23.4	22.3	9
53	2421	Upper Galveston Bay	16512	13.9	25.2	20.0	8
54	2421	Upper Galveston Bay	16516	15.0	23.8	20.9	12
55	2421	Upper Galveston Bay	16563	3.0	23.0	12.6	34
56	2421	Upper Galveston Bay	17091	0.9	25.7	13.4	104
	2421	**Upper Galveston Bay**		**0.0**	**29.8**	**12.4**	**6707**

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
57	2422	Trinity Bay	10657	0.4	24.4	5.4	56
58	2422	Trinity Bay	10658	1.0	14.4	3.0	11
59	2422	Trinity Bay	13314	0.0	31.3	8.5	197
60	2422	Trinity Bay	13315	1.0	24.8	10.4	70
	2422	**Trinity Bay**		**0.0**	**31.3**	**6.8**	**334**

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
61	2423	East Bay	10655	8.1	16.1	12.9	25
62	2423	East Bay	10656	13.1	15.2	14.0	5
63	2423	East Bay	13320	1.0	22.0	8.1	276
64	2423	East Bay	13561	11.0	18.0	14.5	10
65	2423	East Bay	14522	1.0	28.2	14.7	223

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
66	2423	East Bay	14523	1.0	22.4	7.3	228
67	2423	East Bay	14524	1.0	21.2	7.5	226
68	2423	East Bay	14525	1.0	21.2	8.8	205
69	2423	East Bay	14526	1.0	19.5	11.0	205
70	2423	East Bay	14527	1.0	15.0	8.0	125
71	2423	East Bay	14528	1.0	12.7	5.8	107
72	2423	East Bay	14529	2.3	27.3	14.9	121
73	2423	East Bay	14530	4.0	26.3	13.0	107
74	2423	East Bay	14531	0.0	20.5	7.9	288
75	2423	East Bay	14532	0.3	24.3	11.4	247
76	2423	East Bay	14535	1.0	28.1	20.5	140
77	2423	East Bay	14536	1.0	26.3	15.3	137
	2423	**East Bay**	17	**0.0**	**28.2**	**11.5**	**2675**

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
78	2424	West Bay	11415	1.0	25.8	9.5	32
79	2424	West Bay	13321	8.8	33.0	20.6	199
80	2424	West Bay	13322	12.7	30.1	22.5	103
	2424	**West Bay**	3	**1.0**	**33.0**	**17.5**	**334**

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
81	2432	Chocolate Bay	11422	1.0	2.9	1.4	6
82	2432	Chocolate Bay	13346	2.1	30.9	20.3	122
83	2432	Chocolate Bay	15180	8.7	32.9	20.3	10
84	2432	Chocolate Bay	16228	2.1	25.2	16.2	9
	2432	**Chocolate Bay**	4	**1.0**	**32.9**	**14.6**	**147**

	Segment Number	Segment Name	StationID	Minimun	Maximun	Average	Count
85	2439	Lower Galveston Bay	13364	2.8	29.5	18.4	501
	2439	**Lower Galveston Bay**	1	**2.8**	**29.5**	**18.4**	**501**

Appendix C: Bacterial Monitoring Data in Galveston Bay

C.1. TEXAS COMMISSION ON ENVIRONMENTAL QUALITY (TCEQ) DATA IN GALVESTON BAY

Table C.1.1: Statistics of TCEQ Fecal Coliform Count (cfu/ 100ml) at Monitoring Stations located in Upper Galveston Bay (2421)

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
1	2421	13303	UPR GALVESTON BAY HSC CM 63/64	Chambers	15	63	10	2	920	68
2	2421	13312	UPR GAL BAY AT HSC MK 85/86	Chambers	16	57	40	2	540	16
3	2421	14554	UPPER GALVESTON BAY	Chambers	5	21	2	2	540	70
4	2421	14555	UPPER GALVESTON BAY	Chambers	6	23	2	2	540	53
5	2421	14556	UPPER GALVESTON BAY	Chambers	13	36	13	2	240	54
6	2421	14557	UPPER GALVESTON BAY	Chambers	7	51	5	2	1600	67
7	2421	14560	UPPER GALVESTON BAY	Chambers	10	39	8	2	920	119
8	2421	14561	UPPER GALVESTON BAY	Chambers	13	63	13	2	1600	118
9	2421	14562	UPPER GALVESTON BAY	Chambers	10	63	5	2	1600	118
10	2421	14563	UPPER GALVESTON BAY	Chambers	4	16	2	2	350	104
11	2421	14565	UPPER GALVESTON BAY	Chambers	9	45	8	2	1600	116
12	2421	14566	UPPER GALVESTON BAY AT HSC 59	Chambers	4	16	2	2	350	122
13	2421	14569	UPPER GALVESTON BAY	Chambers	5	30	2	2	1600	124
14	2421	14570	UPPER GALVESTON BAY	Chambers	8	58	4	2	1600	119
15	2421	14571	UPPER GALVESTON BAY	Chambers	12	106	8	2	1600	117
16	2421	14572	UPPER GALVESTON BAY	Chambers	15	107	13	2	1600	117
17	2421	14579	UPPER GALVESTON BAY	Chambers	17	76	22	2	920	54
18	2421	14580	UPPER GALVESTON BAY	Chambers	73	247	57	2	1600	54
19	2421	14581	UPPER GALVESTON BAY	Chambers	14	107	11	2	1600	118
20	2421	14582	UPPER GALVESTON BAY	Chambers	6	45	2	2	1600	120
21	2421	14598	UPPER GALVESTON BAY	Chambers	34	175	33	2	1600	119

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
22	2421	17091	UPR GALVESTON BAY AT HSC MK65	Gaines	6	60	2	2	1600	104

Table C.1.2: Statistics of TCEQ Fecal Coliform Count (cfu/ 100ml) at Monitoring Stations located in Trinity Bay (2422)

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
1	2422	13314		Chambers	5	18	20	2	350	54
2	2422	13315	TRINITY BAY AT EXXON C-1	Chambers	4	13	10	2	110	54
3	2422	13318		Chambers	3	4	10	2	8	3
4	2422	14538	TRINITY BAY	Chambers	4	10	2	2	79	54
5	2422	14539	TRINITY BAY	Chambers	4	20	2	2	350	54
6	2422	14540	TRINITY BAY	Chambers	4	11	2	2	240	54
7	2422	14541	TRINITY BAY	Chambers	6	17	2	2	240	74
8	2422	14542	TRINITY BAY AT UMBRELLA POINT	Chambers	5	26	2	2	540	53
9	2422	14543	TRINITY BAY E. HOUSTON POINT	Chambers	8	27	5	2	240	52
10	2422	14544	TRINITY BAY	Chambers	4	9	2	2	79	56
11	2422	14545	TRINITY BAY	Chambers	3	9	2	2	170	54
12	2422	14546	TRINITY BAY AT HOUSTON POINT	Chambers	12	61	13	2	1600	53
13	2422	14547	TRINITY BAY	Chambers	5	50	2	2	1600	76
14	2422	14548	TRINITY BAY AT POINT BARROW	Chambers	7	27	2	2	240	54
15	2422	14549	TRINITY BAY AT CROSS BAYOU	Chambers	10	43	7	2	540	54
16	2422	16838	TRINITY BAY N OF VINGT-ET-UN	Chambers	3	12	2	2	350	51
17	2422	17092	TRINITY BAY AT SEPARATOR C-2	Chambers	6	12	5	2	110	30
18	2422	17093	TRINITY BAY NEAR OLD KELLOW	Chambers	3	5	2	2	49	28
19	2422	17094	TRINITY BAY AT DOUBLE BAYOU	Chambers	4	9	2	2	110	51

Table C.1.3: Statistics of TCEQ Fecal Coliform Count (cfu/ 100ml) at Monitoring Stations located in East Bay (2423)

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
1	2423	13320	EAST BAY MARSH/ELM GROVE POINT	Gaines	4	15	10	2	350	91
2	2423	14522	EAST BAY AT ELM GROVE POINT	Gaines	3	4	2	2	33	88
3	2423	14523	EAST BAY	Gaines	2	3	2	2	17	90
4	2423	14524	EAST BAY E STEPHENSON POINT	Gaines	3	4	2	2	63	91
5	2423	14525	EAST BAY	Gaines	3	7	2	2	70	88
6	2423	14526	EAST BAY	Gaines	4	11	2	2	170	90
7	2423	14527	EAST BAY AT MARSH POINT	Gaines	4	10	2	2	130	68
8	2423	14528	EAST BAY NE OF MARSH POINT	Gaines	5	45	2	2	920	63
9	2423	14529	EAST BAY AT ROBINSON BAYOU	Gaines	4	11	2	2	240	65
10	2423	14530	EAST BAY	Gaines	7	85	2	2	1600	64
11	2423	14531	EAST BAY AT GAS PIPE REEF	Gaines	5	21	2	2	540	106
12	2423	14532	EAST BAY S SMITH POINT	Gaines	4	20	2	2	540	111
13	2423	14535	EAST BAY	Gaines	3	6	2	2	70	65
14	2423	14536	EAST BAY E. TIDE GAUGE PILING	Gaines	3	5	2	2	49	67

Table C.1.4: Statistics of TCEQ Fecal Coliform Count (cfu/ 100ml) at Monitoring Stations located in West Bay (2424)

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
1	2424	13321		Gaines	9	27	7	2	350	38
2	2424	13325	WEST BAY AT CARANCAHUA REEF	Gaines	3	8	2	2	170	39
3	2424	14606	WEST BAY	Brazoria	4	52	2	2	1600	38
4	2424	14607	WEST BAY	Gaines	3	17	2	2	540	38

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
5	2424	14608	WEST BAY	Gaines	10	60	8	2	1600	39
6	2424	14609	WEST BAY	Brazoria	10	105	5	2	1600	38
7	2424	14610	WEST BAY AT ICWW 11	Brazoria	8	72	3	2	1600	38
8	2424	14611	WEST BAY AT ICWW 1	Brazoria	8	34	5	2	540	38
9	2424	14614	WEST BAY	Gaines	3	5	2	2	46	38
10	2424	14615	WEST BAY	Gaines	6	66	5	2	1600	38
11	2424	14616	WEST BAY NEAR JAMACIA BEACH	Gaines	3	12	2	2	350	38
12	2424	14617	WEST BAY	Gaines	6	14	5	2	79	39
13	2424	14618	WEST BAY AT MOUTH OF LAKE COMO	Gaines	3	11	2	2	240	39
14	2424	14619	WEST BAY	Gaines	3	13	2	2	350	39
15	2424	14620	WEST BAY AT N DEER ISLAND	Gaines	11	45	8	2	540	39
16	2424	14621	WEST BAY	Gaines	6	53	4	2	1600	39
17	2424	14622	WEST BAY	Gaines	13	45	13	2	350	37
18	2424	14623	WEST BAY	Gaines	12	24	11	2	79	39
19	2424	15456	WEST BAY AT TIKI ISLAND	Gaines	13	67	8	2	1600	36
20	2424	16839	WEST BAY BETWEEN ICWW CM43/44	Gaines	15	42	14	2	350	36
21	2424	16840	WEST BAY AT BAY HARBOR MARINA	Gaines	3	9	2	2	170	35
22	2424	16841	WEST BAY AT OXEN BAYOU	Gaines	4	8	2	2	49	36
23	2424	16842	WEST BAY SW OF NORTH DEER IS.	Gaines	7	17	5	2	170	34
24	2424	16843	WEST BAY AT MAGGIE'S COVE	Gaines	3	3	2	2	17	35
25	2424	16844	WEST BAY SOUTH OF CM59	Gaines	7	30	5	2	540	36

Table C.1.5: Statistics of TCEQ Fecal Coliform Count (cfu/ 100ml) at Monitoring Stations located in Lower Galveston Bay (2439)

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
1	2439	13364	GALVESTON BAY AT CM 2	Gaines	4	15	10	2	170	18
2	2439	13366	GALV. BAY BTWN DOLLAR PT/HSC	Gaines	5	31	2	2	1600	125
3	2439	13367		Gaines	4	7	10	2	22	15
4	2439	13372		Gaines	3	13	2	2	350	49
5	2439	14533	L. GALVESTON BAY BAFFLE/ELM GV	Gaines	2	3	2	2	26	88
6	2439	14558	GALVESTON BAY	Gaines	6	33	2	2	920	90
7	2439	14559	LOWER GALVESTON BAY	Gaines	6	37	2	2	920	99
8	2439	14564	LOWER GALVESTON BAY	Gaines	4	17	2	2	920	126
9	2439	14567	LOWER GALVESTON BAY	Gaines	3	12	2	2	350	110
10	2439	14568	LOWER GALVESTON BAY AT HSC 53	Gaines	4	12	2	2	350	123
11	2439	14573	LOWER GALVESTON BAY	Gaines	6	63	2	2	1600	118
12	2439	14574	LOWER GALVESTON BAY	Gaines	5	34	2	2	1600	121
13	2439	14575	LOWER GALVESTON BAY AT HSC 35	Gaines	4	20	2	2	920	103
14	2439	14576	LOWER GALVESTON BAY	Gaines	5	35	2	2	1600	122
15	2439	14577	LOWER GALVESTON BAY	Gaines	6	48	2	2	1600	119
16	2439	14578	LOWER GALVESTON BAY	Gaines	17	120	13	2	1600	121
17	2439	14584	LOWER GALVESTON BAY	Gaines	5	35	2	2	1600	106
18	2439	14587	LOWER GALVESTON BAY AT HSC 49	Gaines	4	26	2	2	1600	122
19	2439	14588	LOWER GALVESTON BAY AT HSC 43	Gaines	4	24	2	2	1600	123
20	2439	14591	LOWER GALVESTON BAY	Gaines	3	6	2	2	79	48
21	2439	14592	LOWER GALVESTON BAY	Gaines	4	6	2	2	49	49
22	2439	14593	LOWER GALVESTON BAY	Gaines	3	16	2	2	350	49
23	2439	14594	LOWER GALVESTON BAY	Gaines	4	9	2	2	79	45
24	2439	14595	LOWER GALVESTON BAY	Gaines	8	18	8	2	240	47

	Segment Number	Station Number	Description	County	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
25	2439	14596	LOWER GALVESTON BAY AT WWTP	Gaines	9	20	8	2	170	47
26	2439	14597	LOWER GALVESTON BAY AT HSC 25	Gaines	4	15	2	2	350	49
27	2439	14884	LOWER GALVESTON BAY	Gaines	5	31	2	2	1600	122
28	2439	16522	LOWER GALVESTON BAY (98GB029)	Gaines	5	11	2	2	110	77

C.2. Texas Department of Health (TDH) Data in Galveston Bay

Table C.2.1: Statistics of TDH Fecal Coliform Count at Monitoring Stations located in East Bay (2423)

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
1	EAS	00143	29.48	-94.68	Elm Grove Point	9.5	2.8	2	2	540	119
2	EAS	00147	29.50	-94.70	Two miles northwest of Elm	2.8	2.3	2	2	23	120
3	EAS	00151	29.53	-94.69	North side of lease #299,	4.7	2.8	2	2	63	120
4	EAS	00168	29.50	-94.60	Between Yates Bayou & Big	8.9	3.6	2	2	170	115
5	EAS	00170	29.53	-94.62	Two miles west of Marsh Po	17.0	4.1	2	2	350	118
6	EAS	00173	29.55	-94.63	Between Stephenson Point &	20.9	4.1	2	2	920	117
7	EAS	00175	29.53	-94.58	Marsh Point	31.5	4.4	2	2	1600	92
8	EAS	00188	29.54	-94.54	0.5 miles WNW of Frozen Po	52.9	6.5	2	2	920	84
9	EAS	00190	29.56	-94.57	Robinson Bayou	36.8	4.4	2	2	920	88
10	EAS	00191	29.53	-94.52	Between Frozen Point & Rol	95.1	8.3	2	2	1600	85
11	EAS	00228	29.52	-94.79	Two miles SSW of Smith Poi	20.0	5.1	2	2	540	136
12	EAS	00230	29.50	-94.77	1.5 miles south of Smith P	19.0	4.3	2	2	540	145
13	EAS	00239	29.47	-94.74	South side of Hanna Reef	9.8	4.1	2	2	130	124
14	EAS	00275	29.44	-94.72	Sievers Cut	3.5	2.5	2	2	41	113
15	EAS	00320	29.42	-94.77	Baffle Point	4.4	2.8		2	70	133
16	EAS	0138A	29.52	-94.76	0.5 miles west of tripod	7.0	3.4	2	2	79	82
17	EAS	0138C	29.52	-94.75	Northwest of tripod southe	8.3	3.2	2	2	240	85

Table C.2.2: Statistics of TDH Fecal Coliform Count at Monitoring Stations located in Galveston Bay (2421 & 2439)

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
18	GAL	00084	29.56	-94.86	4 miles WNW of Smith Pt.	17.8	5.3	2	2	540	96
19	GAL	00116	29.61	-94.92	Black and white diamond ma	25.9	6.8	5	2	540	69
20	GAL	00119	29.63	-94.94	E of Atkinson Is./1.5 mile	39.1	15.0	15	2	240	70
21	GAL	00137	29.55	-94.79	Smith Pt. in Trinity River	45.8	7.4	5	2	1600	89
22	GAL	00198	29.53	-94.78	Between Leases 412-A & 387	30.6	5.8	2	2	920	110
23	GAL	00199	29.54	-94.79	Smith Point Shellfish Mark	36.5	5.8	2	2	920	129
24	GAL	00209	29.61	-94.95	Houston Ship Channel Marke	39.1	10.6	10	2	920	159
25	GAL	00213	29.65	-95.00	100 yards off Sylvan Beach	57.0	13.5	13	2	1600	148
26	GAL	00216	29.60	-94.97	Between Red Bluff and Hous	54.0	10.0	5	2	1600	150
27	GAL	00226	29.54	-94.84	Pipe @ platform, 2.5 miles	17.0	4.6	2	2	350	138
28	GAL	00244	29.48	-94.83	Lease 423-A, SE corner	21.1	4.4	2	2	920	164
29	GAL	00251	29.56	-94.92	Houston Ship Channel Marke	44.1	5.6	2	2	1600	159
30	GAL	00256	29.59	-94.99	150 yards SW of Surf Oaks	41.1	9.3	8	2	1600	147
31	GAL	00263	29.53	-94.90	Houston Ship Channel Marke	24.7	4.8	2	2	1600	165
32	GAL	00280	29.46	-94.78	2 miles WSW of Hanna's Ree	12.1	3.4	2	2	350	144
33	GAL	00284	29.49	-94.87	Houston Ship Channel Marke	21.5	4.4	2	2	1600	167
34	GAL	00286	29.51	-94.89	West Pass, between Red Fis	40.1	5.4	2	2	1600	166
35	GAL	00291	29.54	-94.96	3 miles from Red Bluff Pt.	53.7	8.3	5	2	1600	159
36	GAL	00296	29.55	-94.99	Clear Lake Channel Marker	95.8	13.3	11	2	1600	152
37	GAL	00302	29.53	-95.00	Between Kemah & Bayview, 7	102.3	16.4	13	2	1600	148

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
38	GAL	00305	29.51	-94.96	HL&P discharge channel	108.3	14.6	11	2	1600	153
39	GAL	00308	29.50	-94.91	0.5 miles NW of Eagle Pt.	54.7	6.8	3	2	1600	156
40	GAL	0308A	29.49	-94.90	Eagle Pt., Between Wreck M	50.3	6.3	2	2	1600	167
41	GAL	00312	29.47	-94.85	Houston Ship Channel, west	30.8	4.0	2	2	1600	167
42	GAL	00326	29.45	-94.84	Houston Ship Channel Marke	24.6	4.0	2	2	1600	167
43	GAL	00329	29.48	-94.89	1.8 miles ESE of Eagle Poi	38.3	5.0	2	2	1600	166
44	GAL	00331	29.48	-94.91	Midway between Eagle and A	76.2	7.6	2	2	1600	158
45	GAL	00332	29.46	-94.90	Dickinson Bay Channel Mark	36.0	5.0	2	2	1600	163
46	GAL	00345	29.41	-94.82	Houston Ship Channel Marke	17.1	3.6	2	2	920	128
47	GAL	00349	29.44	-94.88	Dollar Point, approximatel	39.5	4.9	2	2	1600	164
48	GAL	00350	29.45	-94.90	Midway between Moses Lake	44.5	6.0	2	2	1600	161
49	GAL	00352	29.45	-94.91	600 yards off Moses Lake T	66.2	7.6	2	2	1600	162
50	GAL	00354	29.47	-94.95	Dickinson Bay Channel Mark	144.9	18.6	13	2	1600	157
51	GAL	00361	29.69	-94.96	Cedar Bayou Channel Marker	77.1	19.8	23	2	920	69
52	GAL	00362	29.67	-94.93	Cedar Bayou Channel Marker	244.6	76.6	70	2	1600	70
53	GAL	00A89	29.34	-94.89	Campbell Bayou	5.6	3.0	2	2	79	63
54	GAL	00A91	29.38	-94.88	Mouth of Texas City Turnin	6.2	3.6	2	2	49	65
55	GAL	0A114	29.40	-94.84	Half Moon Shoal	12.1	3.1	2	2	350	70
56	GAL	0A120	29.33	-94.84	Marker #4, W of ICW Marker	8.1	4.0	2	2	79	60
57	GAL	0A122	29.31	-94.83	Pelican Island, W of Bascu	17.9	7.7	8	2	240	62
58	GAL	A122C	29.30	-94.83	100 yards NE of the Main G	18.1	8.9	8	2	170	62
59	GAL	0A131	29.37	-94.80	Houston Ship Channel Marke	10.9	3.4	2	2	350	75

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
60	GAL	0A137	29.34	-94.77	Houston Ship Channel Marke	8.8	2.9	2	2	350	66
61	GAL	0Y300	29.55	-95.02	Clear Lake Channel Marker	173.0	36.1	33	2	1600	151

Table C.2.3: Statistics of TDH Fecal Coliform Count at Monitoring Stations located in Trinity Bay (2422)

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
62	TRI	00058	29.63	-94.76	Double Bayou Channel Marke	9.5	4.0	2	2	79	68
63	TRI	0058B	29.68	-94.76	Separator C-2	16.4	4.0	2	2	350	39
64	TRI	00060	29.61	-94.72	Lone Oak Bayou at railroad	17.2	3.6	2	2	240	70
65	TRI	00061	29.59	-94.74	Second tripod NNE of Vingt	16.4	5.6	2	2	350	94
66	TRI	00065	29.61	-94.82	Middle of Trinity Bay at c	23.8	5.7	3	2	540	70
67	TRI	00070	29.67	-94.85	Umbrella Point	27.9	7.9	7	2	240	70
68	TRI	00071	29.65	-94.89	2.3 miles east of Houston	9.1	3.9	2	2	79	68
69	TRI	00073	29.63	-94.85	Big Yellow Platform (Old Y	8.1	3.3	2	2	170	71
70	TRI	00088	29.62	-94.85	One mile SSW of Big Yellow	6.7	3.7	2	2	49	69
71	TRI	00081	29.57	-94.76	First tripod north of Ving	60.8	12.7	13	2	1600	38
72	TRI	00095	29.65	-94.92	Houston Point	33.7	4.9	2	2	1600	69
73	TRI	00100	29.59	-94.87	Little Yellow Separator Pl	10.8	3.3	2	2	350	95
74	TRI	00108	29.56	-94.78	North side of Vingt-et-un	10.9	4.1	2	2	110	68
75	TRI	0023A	29.66	-94.79	Between Umbrella Point & D	13.1	5.7	5	2	110	69
76	TRI	0058F	29.64	-94.71	Double Bayou Channel Marke	8.6	3.9	2	2	110	69
77	TRI	1011E	29.73	-94.82	Point Barrow, tall piling	24.5	6.5	4	2	240	68
78	TRI	1316B	29.70	-94.74	Anahuac Channel Marker #1	17.3	5.1	2	2	350	69
79	TRI	2223C	29.76	-94.77	Cross Point between white	36.5	9	7	2	540	68

Table C.2.4: Statistics of TDH Fecal Coliform Count at Monitoring Stations located in West Bay (2424)

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
80	WES	00025	29.15	-95.12	West of Fish Haven Pilings	40.9	4	2	2	1600	53
81	WES	00036	29.14	-95.08	Entrance of Bay Harbor Mar	8.5	3	2	2	170	52
82	WES	00038	29.14	-95.07	Terramar Beach Channel Mar	14.5	3	2	2	540	52
83	WES	00070	29.28	-94.96	0.7 miles south of ICW Mar	28.1	9	8	2	540	53
84	WES	071IC	29.28	-94.96	Between ICW Markers #59 &	8.4	4	2	2	79	53
85	WES	00077	29.25	-94.94	Mouth of Oxen Bayou	82.4	9	5	2	1600	53
86	WES	0079W	29.28	-94.93	550 yards southwest of Nor	26.8	9	7	2	350	50
87	WES	0082A	29.30	-94.90	Tiki Island Channel mouth	55.4	13	11	2	1600	53
88	WES	0083A	29.29	-94.92	Between ICW Markers #43 &	56.3	15	14	2	920	52
89	WES	000A8	29.15	-95.15	ICW Marker #22 at Chocolat	82.4	8	5	2	1600	53
90	WES	00A19	29.16	-95.13	ICW Marker #11 at Chocolat	58.1	8	4	2	1600	53
91	WES	00A23	29.17	-95.11	ICW Marker #1 at Chocolate	33.8	3	5	2	540	53
92	WES	00A46	29.16	-95.05	End of Sea Isle Channel	3.4	3	2	2	33	52
93	WES	00A47	29.17	-95.03	Mouth of Maggies Cove	4.3	3	2	2	33	52
94	WES	00A49	29.20	-95.02	Between Alligator Point &	4.3	6	2	2	46	52
95	WES	00A52	29.24	-95.01	Carancahua Lake & ICW	53.1	3	5	2	1600	52
96	WES	00A58	29.21	-95.00	1,000 yards north of Jamai	10.7	3	2	2	350	52
97	WES	00A59	29.22	-95.00	Northeast of Carancahua Re	7.1	7	2	2	170	53
98	WES	00A61	29.27	-94.99	Greens Lake & ICW	14.2	3	5	2	79	53
99	WES	00A67	29.23	-94.96	Mouth of Lake Como and mid	9.5	3	2	2	240	53
100	WES	00A69	29.24	-94.96	North of Hoeckers Point at	12.3	13	2	2	350	53
101	WES	00A73	29.28	-94.95	ICW Marker #15 at North De	75.3	7	11	2	1600	53
102	WES	00A79	29.28	-94.92	Between North & South Deer	43.2	13	5	2	1600	53

	Bay Code	Station Number	Latitude	Longitude	Description of Station	Arithmetic Mean	Geometric Mean	Median	Minimum	Maximum	Count of Data Values
103	WES	00A85	29.28	-94.90	Range Marker D between Sou	42.1	12	11	2	350	51
104	WES	00A86	29.30	-94.89	Galveston Causeway & ICW	45.4	9	11	2	920	53
105	WES	0A105	29.28	-94.88	Teichman Point	27.6	9	7	2	350	52

Appendix D: Bacterial Monitoring Data in Study Area Watershed

[Source: Texas Commission of Environmental Quality (TCEQ) database. Storet Code: 31616. Sampling Method: Membrane Filtration Method.]

Table D.1: Statistics of fecal coliform count (cfu/100 ml) at monitoring stations located in study area watershed:

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
1	10337	189	3367	123	2	52800	21
2	10345	27	86	25	3	2920	101
3	10391	33	129	36	2	1580	79
4	10394	44	115	36	2	1080	55
5	10395	53	140	54	1	1240	78
6	10441	179	877	129	4	14008	84
7	10442	600	2142	840	19	10900	21
8	10443	184	240	106	67	520	6
9	10449	259	994	212	23	32921	74
10	10453	128	591	108	4	13450	59
11	10457	223	314	210	33	880	21
12	10485	138	223	145	20	660	27
13	10530	416	605	235	130	1500	4
14	10563	39	105	33	3	1640	41
15	10566	32	76	37	3	324	31
16	10570	89	138	80	11	573	39
17	10575	37	93	57	3	600	31
18	10580	24	47	22	3	230	26
19	10599	31	126	27	1	1060	30
20	10602	38	112	29	3	1200	28
21	10607	139	385	104	19	4420	30
22	10609	96	245	82	11	1640	18
23	10640	19	49	20	3	410	27
24	10642	24	125	13	3	600	9
25	10643	112	217	102	10	740	18
26	10652	14	32	13	3	197	17
27	10657	10	10	10	10	10	1
28	10658	10	10	10	10	10	1
29	10668	29	63	31	3	370	23
30	10669	33	243	21	1	2900	30

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
31	10679	13	31	10	3	217	28
32	10683	35	135	31	3	1200	27
33	10685	43	123	33	3	750	22
34	10686	20	241	10	1	3000	30
35	10688	93	103	103	60	145	2
36	10695	34	37	40	20	60	5
37	10696	185	1369	65	10	11000	10
38	10698	184	399	171	20	2300	14
39	10700	517	3113	75	50	11000	4
40	10701	187	2360	100	10	13000	7
41	10892	10	10	10	10	10	1
42	10894	69	253	35	10	2100	30
43	10896	46	277	45	10	6200	32
44	10897	30	727	15	5	5700	8
45	10898	21	40	20	10	490	34
46	10899	11	12	10	5	50	64
47	10909	30	45	30	10	150	12
48	10911	16	23	10	6	100	17
49	10913	31	131	20	10	1680	17
50	10914	53	239	50	6	4500	70
51	11095	380	380	380	380	380	1
52	11111	10	10	10	10	10	1
53	11120	10	10	10	10	10	1
54	11124	1296	6977	860	120	190000	65
55	11125	615	9444	420	9	200000	69
56	11126	1470	7103	1000	10	120000	70
57	11127	706	5364	660	10	84000	31
58	11128	1886	5089	1700	120	46000	37
59	11129	724	9900	500	9	240000	76
60	11130	3373	3580	3100	2300	5700	5
61	11131	3367	18667	2650	10	200000	44
62	11132	1277	5526	1600	54	70000	69
63	11133	3508	9296	3600	160	47000	35
64	11135	2469	17172	2600	9	200000	78
65	11138	10891	37012	11000	160	200000	35
66	11139	2769	11006	2950	18	200000	70
67	11140	4546	16429	4700	120	150000	75
68	11148	22094	67868	45000	650	200000	70
69	11163	652	3059	510	45	52000	66
70	11169	3728	16744	3500	36	200000	69

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
71	11187	43	158	36	9	3500	90
72	11188	2680	11522	2500	45	200000	69
73	11193	49	109	50	1	460	29
74	11198	33	131	20	1	1750	28
75	11200	34	847	30	1	21000	28
76	11201	20	93	20	1	540	27
77	11204	58	291	110	1	2000	175
78	11208	13	35	7	2	150	19
79	11211	40	136	32	1	2000	172
80	11212	37	112	40	1	2000	174
81	11213	243	1803	195	9	56000	86
82	11235	142	310	120	18	4400	90
83	11245	10	10	10	10	10	1
84	11252	59	60	60	50	70	2
85	11252			33	50	70	2
86	11254	26	326	20	1	6000	23
87	11258	335	470	470	140	800	2
88	11264	103	350	80	10	3900	25
89	11271	355	1950	300	1	22000	26
90	11272	400	400	400	400	400	1
91	11273	1106	1880	1880	360	3400	2
92	11275	2000	2000	2000	2000	2000	1
93	11277	415	947	340	36	4700	30
94	11279	352	2320	365	3	65000	74
95	11283	374	2616	350	1	20700	26
96	11284	18974	33000	33000	6000	60000	2
97	11287	3098	3200	3200	2400	4000	2
98	11292	457	2326	400	1	21500	28
99	11293	706	1894	485	53	9000	8
100	11296	2000	2900	2900	800	5000	2
101	11298	561	3253	370	31	35000	35
102	11299	5044	5050	5050	4800	5300	2
103	11302	717	3064	395	81	29000	36
104	11304	905	4118	690	36	36000	29
105	11306	3230	18394	3000	72	200000	30
106	11307	900	900	900	900	900	1
107	11309	7527	20004	6500	63	200000	44
108	11312	232	1283	165	9	21000	78
109	11314	70	70	70	70	70	1
110	11324	35	35	35	35	35	1

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
111	11328	1064	4515	940	9	79000	85
112	11332	30	30	30	30	30	1
113	11333	502	1711	325	30	24000	64
114	11334	91	486	72	9	11000	88
115	11336	131	567	110	9	31000	89
116	11338	139	143	140	100	190	3
117	11345	3164	13645	2350	340	200000	38
118	11347	3218	8572	2700	210	200000	85
119	11351	478	11088	3700	63	200000	115
120	11353	2016	7353	1450	160	57000	36
121	11354	1076	2661	610	150	8100	8
122	11356	1828	4914	1700	110	44000	88
123	11357	1106	3483	820	10	45000	36
124	11358	6000	6000	6000	6000	6000	1
125	11359	1330	4882	1200	10	41000	36
126	11360	1346	5633	1250	140	87000	98
127	11361	1839	5881	1500	150	26000	36
128	11362	1317	5457	800	90	40000	37
129	11363	952	4878	495	72	59000	36
130	11364	529	1771	475	18	58000	90
131	11368	420	420	420	420	420	1
132	11369	138	848	155	3	11000	38
133	11370	102	715	160	3	8200	39
134	11371	415	3131	330	4	120000	79
135	11372	6	19	4	4	120	8
136	11373	8	722	4	3	5750	8
137	11376	5	5	5	4	6	7
138	11377	310	310	310	310	310	1
139	11378	265	265	265	265	265	1
140	11381	850	850	850	850	850	1
141	11387	4280	10429	3900	220	60000	80
142	11390	1997	5927	1800	99	89000	42
143	11391	2485	3687	1900	520	11000	6
144	11398	5000	5000	5000	5000	5000	1
145	11400	114	236	90	10	1300	29
146	11404	600	4023	4023	45	8000	2
147	11409	261	1157	205	14	12000	34
148	11415	189	523	230	3	5000	37
149	11425	628	3797	470	40	24000	17
150	11436	343	2120	300	5	24000	39

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
151	11446	242	1069	180	20	13000	29
152	11447	292	2134	170	9	30000	49
153	11448	442	5113	200	9	200000	86
154	11449	479	2298	230	20	16000	37
155	11450	832	3856	500	20	30000	42
156	11451	1181	5061	800	70	24000	13
157	11452	430	1971	300	27	29000	47
158	11455	44	300	20	5	5000	38
159	11460	232	1427	170	5	16000	104
160	11461	292	1583	230	20	16000	44
161	11462	230	1855	170	5	16000	83
162	11464	244	971	170	5	16000	81
163	11465	348	2004	300	40	16000	19
164	11467	478	1503	300	5	24000	39
165	11503	168	609	150	9	4500	11
166	11516	51	270	50	4	1200	9
167	11518	427	705	630	24	1200	16
168	11756	307	494	284	8	2500	33
169	11843	94	394	72	4	1200	13
170	11850	83	364	68	4	1200	29
171	12074	234	543	165	16	1200	7
172	12079	1450	1450	1450	1450	1450	1
173	12083	377	2074	342	4	22000	14
174	12086	178	471	220	4	4600	29
175	12087	195	458	203	12	1200	10
176	12090	86	124	80	24	300	9
177	13298	5	8	3	3	50	27
178	13300	5	10	3	3	100	27
179	13302	16	65	17	3	840	27
180	13303	10	10	10	10	10	1
181	13305	10	10	10	10	10	1
182	13306	10	10	10	10	10	1
183	13307	30	30	30	30	30	1
184	13312	40	40	40	40	40	1
185	13314	20	20	2	20	20	1
186	13315	10	10	2	10	10	1
187	13318	10	10	10	10	10	1
188	13320	10	10	2	10	10	1
189	13336	77	103	103	35	170	2
190	13339	133	150	150	80	220	2

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
191	13341	10	10	10	10	10	1
192	13342	428	440	440	340	540	2
193	13344	50	130	130	10	250	2
194	13361	30	93	20	10	1300	28
195	13364	10	10	10	10	10	1
196	13367	10	10	2	10	10	1
197	13461	5	10	3	3	53	26
198	13462	8	13	3	3	27	4
199	13463	4	4	3	2	17	16
200	13625	65	234	68	3	1344	28
201	13778	971	7668	3500	3	45000	39
202	13781	126	398	84	4	3840	71
203	13945	10	40	8	2	260	17
204	13951	11	96	10	1	1400	17
205	14148	50	202	47	1	2000	168
206	14229	578	2549	500	20	17000	38
207	14494	400	4065	109	108	15907	4
208	14495	496	888	153	146	1820	4
209	14503	1401	3689	1200	26	13533	18
210	14964	528	6978	400	30	103000	21
211	14990	422	2890	293	20	43275	49
212	15107	209	823	156	20	11500	71
213	15343	23	43	22	2	244	29
214	15345	106	307	87	8	2440	28
215	15346	99	305	94	4	3180	30
216	15352	120	546	152	1	3900	39
217	15353	270	802	210	30	6900	45
218	15354	118	626	100	2	7633	18
219	15367	47	243	39	3	3860	30
220	15438	200	200	200	200	200	1
221	15439	500	500	500	500	500	1
222	15458	332	1509	220	20	23000	47
223	15520	488	1621	500	9	12000	14
224	15545	63	63	63	63	63	1
225	15742	916	4260	560	35	24600	16
226	15825	7248	14346	6900	290	100000	34
227	15826	3886	9203	3100	500	86000	44
228	15827	4911	10172	6200	640	57000	29
229	15828	12000	12000	12000	12000	12000	1
230	15829	1174	3730	650	110	26000	30

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
231	15830	1248	2070	800	620	8000	6
232	15831	1042	2382	865	63	16000	34
233	15832	3052	3075	2750	2700	3700	4
234	15841	2345	6951	2050	120	35000	38
235	15843	2946	11494	2300	100	200000	38
236	15844	1956	12660	2100	72	200000	29
237	15845	1504	5822	1300	150	55000	36
238	15846	1270	4983	1065	10	56000	36
239	15847	867	4924	560	36	75000	69
240	15848	1465	6548	940	81	60000	35
241	15849	910	6015	735	9	80000	34
242	15850	4268	12271	3900	200	84000	35
243	15851	3648	10306	4100	54	60000	35
244	15852	5241	16443	4200	230	120000	35
245	15853	5670	19392	5100	130	200000	35
246	15854	6149	17754	4700	45	180000	35
247	15855	4339	14190	3700	90	200000	35
248	15859	4176	14963	3300	27	200000	35
249	15860	2415	2500	2050	1800	3800	6
250	15861	1814	6808	1700	45	47000	14
251	15862	696	4036	455	81	54000	30
252	15863	2275	7563	1550	150	73000	40
253	15864	1396	6846	1015	9	70000	30
254	15867	432	6863	520	18	200000	35
255	15868	2469	14323	3150	10	200000	44
256	15869	16229	63198	20500	10	200000	72
257	15870	5861	6860	8000	2600	12000	5
258	15871	3137	3180	3100	2500	4000	5
259	15872	3923	7180	4100	600	22000	5
260	15873	840	3496	1250	9	17000	30
261	15874	1732	2090	1400	650	3600	5
262	15875	1786	15822	2600	9	200000	35
263	15876	3576	10281	4200	240	110000	35
264	15877	3264	13727	2800	140	200000	35
265	15878	1720	4981	2550	18	34000	36
266	15941	438	1992	500	1	16000	38
267	16039	19635	23200	22400	8800	38400	3
268	16040	383	1787	370	3	22000	28
269	16041	2047	27110	1200	46	337000	33
270	16049	592	4627	380	26	59600	20

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
271	16052	1002	6920	1200	45	111505	21
272	16053	885	2735	1040	39	17000	21
273	16054	916	10145	721	36	167000	21
274	16055	707	6468	430	4	52000	14
275	16056	1351	5354	800	230	46600	21
276	16057	413	1225	420	49	8400	21
277	16059	641	2723	586	30	25000	21
278	16060	186	1443	140	4	16600	33
279	16061	13103	15300	15300	7400	23200	2
280	16077	332	445	195	190	1100	4
281	16078	227	718	50	20	1900	4
282	16079	214	265	140	90	560	4
283	16080	312	580	145	80	1700	4
284	16081	116	413	83	20	3700	15
285	16086	335	740	740	80	1400	2
286	16087	263	438	110	100	1200	4
287	16096	9	25	13	1	60	3
288	16099	550	833	215	180	1700	4
289	16123	85	197	100	1	660	19
290	16127	27	27	27	27	27	1
291	16148	26	54	15	5	200	8
292	16355	223	540	153	20	1200	10
293	16387	96	503	52	4	2800	14
294	16398	104	209	90	8	1200	26
295	16399	124	501	96	4	5300	31
296	16469	1179	4210	1100	5	24000	38
297	16470	660	2432	500	5	24000	38
298	16471	536	2771	500	5	24000	38
299	16472	312	2409	230	10	24000	39
300	16473	701	2534	400	70	24000	38
301	16475	829	5066	650	10	90000	38
302	16476	328	3206	225	10	30000	38
303	16477	585	2814	300	10	24000	38
304	16478	998	3827	700	80	16000	21
305	16479	8673	35619	5600	220	200000	35
306	16481	28	64	20	10	350	9
307	16482	27	48	20	10	180	9
308	16483	21	33	10	10	100	9
309	16484	27	93	15	10	640	9
310	16485	587	2159	700	20	30000	29

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
311	16486	3674	7230	3000	110	24000	30
312	16487	28	36	20	10	110	16
313	16488	36	92	20	5	1300	37
314	16489	131	412	110	10	3000	31
315	16490	248	1648	230	5	24000	37
316	16491	474	2318	500	3	24000	38
317	16493	760	3678	500	40	24000	36
318	16494	35	105	20	10	800	28
319	16536	42	90	20	10	500	30
320	16537	21	29	20	10	230	29
321	16538	24	36	20	10	300	30
322	16539	23	37	20	10	300	30
323	16540	27	49	20	10	500	30
324	16541	35	67	20	10	500	29
325	16542	38	105	20	10	800	30
326	16543	44	83	20	10	500	29
327	16544	52	103	20	10	500	30
328	16545	62	231	40	10	2200	27
329	16546	19	29	20	8	300	27
330	16547	26	63	20	1	800	28
331	16548	19	25	20	10	170	26
332	16549	24	35	20	10	220	29
333	16550	22	70	20	10	1300	27
334	16551	27	54	20	10	500	28
335	16552	30	82	20	10	800	29
336	16553	17	20	20	10	70	27
337	16554	115	331	130	10	2400	25
338	16555	20	26	20	10	110	28
339	16556	39	98	20	10	800	27
340	16559	48	272	20	10	5000	30
341	16560	42	132	20	10	900	29
342	16561	26	37	20	10	230	29
343	16562	188	934	130	2	16000	37
344	16563	62	299	40	10	5000	28
345	16564	52	212	40	10	3000	30
346	16565	18	22	20	10	130	27
347	16566	21	39	20	10	500	28
348	16567	19	67	20	10	1300	26
349	16568	16	17	20	10	20	27
350	16569	18	21	20	10	90	27

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
351	16570	23	32	20	10	130	14
352	16571	49	202	20	10	3000	29
353	16572	130	947	110	20	9000	29
354	16573	84	772	70	10	16000	29
355	16575	250	1214	200	10	16000	38
356	16576	269	2234	120	20	24000	38
357	16577	224	1890	130	10	24000	38
358	16589	1238	15960	860	36	200000	53
359	16590	791	15711	475	9	200000	68
360	16591	1381	19484	985	10	380000	38
361	16592	3533	14285	3200	72	160000	67
362	16593	3532	18294	2950	68	200000	68
363	16594	7175	23370	5750	90	200000	68
364	16595	14105	57596	14000	10	200000	68
365	16596	4455	16748	3800	10	200000	66
366	16597	5421	24871	4200	150	290000	67
367	16598	870	870	870	870	870	1
368	16617	144	748	100	10	9200	27
369	16618	41	158	30	1	1000	26
370	16619	60	351	30	1	4000	24
371	16620	324	1595	200	1	17500	21
372	16621	58	546	30	10	9100	28
373	16622	29	841	30	1	20800	27
374	16629	82	157	83	10	790	28
375	16630	88	184	90	10	880	28
376	16631	79	174	75	10	880	28
377	16632	96	196	100	10	940	28
378	16634	97	180	115	10	900	28
379	16636	460	460	460	460	460	1
380	16637	2906	6770	2100	210	37000	36
381	16647	2979	5548	1550	590	15000	6
382	16648	3647	21689	5450	390	200000	86
383	16649	5465	38419	4800	9	280000	68
384	16650	11206	52214	21000	10	440000	69
385	16651	19706	92459	31500	9	480000	66
386	16652	2046	10327	2100	10	200000	70
387	16653	1874	22816	1000	81	270000	69
388	16654	4487	32051	4400	230	710000	70
389	16655	1130	4850	1200	27	90000	64
390	16656	349	2261	230	9	71000	64

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
391	16657	1727	10498	1450	27	200000	70
392	16658	7915	38331	6950	180	720000	66
393	16659	4346	38670	2750	27	200000	66
394	16660	2026	10226	1300	63	180000	65
395	16661	1360	5186	950	100	44000	66
396	16662	2299	17306	2200	90	200000	67
397	16663	1378	14913	665	72	200000	66
398	16664	40221	111127	110000	330	200000	66
399	16665	1519	9354	1300	54	200000	69
400	16666	2377	13226	2700	54	200000	69
401	16667	759	8533	600	24	200000	69
402	16670	23	32	20	10	130	29
403	16671	52	382	40	10	9000	30
404	16672	48	94	20	10	500	30
405	16674	10	10	10	10	10	1
406	16675	4958	31716	2950	90	440000	66
407	16676	1011	10280	520	9	150000	67
408	16679	112	1059	40	5	16000	37
409	16690	372	806	373	27	3600	14
410	16711	288	312	312	193	431	2
411	16878	4	4	4	4	4	1
412	16979	153	1684	40	20	16000	42
413	17068	425	2531	170	40	16000	13
414	17069	2232	12104	3000	80	90000	13
415	17070	1539	3129	1100	230	16000	18
416	17071	939	2163	535	170	7000	10
417	17072	230	2464	75	20	16000	12
418	17073	453	2387	365	20	24000	14
419	17074	736	4172	800	40	30000	13
420	17076	889	3854	500	130	16000	13
421	17077	385	3121	130	20	16000	13
422	17078	231	417	190	20	800	6
423	17079	228	238	230	130	300	5
424	17080	22	23	20	20	40	14
425	17081	20	20	20	20	20	14
426	17082	25	29	20	20	130	16
427	17083	27	32	20	20	80	17
428	17084	27	35	20	20	170	16
429	17371	849	975	750	300	1200	4
430	17372	208	219	219	150	288	2

	Station Number	Geometric Mean	Arithmetic Mean	Median	Minimum	Maximum	Count of Data Values
431	17373	76	76	76	76	76	1
432	17380	184	252	284	52	420	3
433	17381	1166	1167	1200	1100	1200	3
434	17382	849	975	750	300	1200	4
435	17426	7	7	7	7	7	1
	Entire Dataset				**1**	**720000**	**13653**

Appendix E: Visual Basic Scripts for Computing Geometric Mean and Median

Visual Basic script for Excel to compute Geometric Mean value of fecal coliform dataset at each monitoring station:

```
Sub massageData()
Dim rowCount, stationCount As Integer
Dim count As Integer
rowCount = 0
Dim staionID As Integer
staionCount = 0
Dim totalSum As Double
Dim totalProd As Double
Dim invCount As Double

Do While ActiveCell.Offset(rowCount, 0) <> ""
   stationID = ActiveCell.Offset(rowCount, 0)
   count = 0
   totalSum = 0
   totalProd = 1


   Do
      totalSum = totalSum + ActiveCell.Offset(rowCount, 1).Value

      On Error Resume Next
      totalProd = totalProd * ActiveCell.Offset(rowCount, 1).Value

      count = count + 1
      rowCount = rowCount + 1
   Loop While ActiveCell.Offset(rowCount, 0) = stationID

   invCount = 1 / count

   ActiveCell.Offset(stationCount, 3).Value = stationID
   ActiveCell.Offset(stationCount, 4).Value = count
   ActiveCell.Offset(stationCount, 5).Value = invCount
   ActiveCell.Offset(stationCount, 6).Value = totalSum
   ActiveCell.Offset(stationCount, 7).Value = totalProd

   stationCount = stationCount + 1
```

```
   Loop

End Sub
Sub massageErrorData()

Dim rowCount, stationCount As Integer
Dim count As Integer
rowCount = 0
Dim staionID As Integer
staionCount = 0
Dim totalSum As Double
Dim totalProd As Double
Dim invCount As Double

Do While ActiveCell.Offset(rowCount, 0) <> ""
   stationID = ActiveCell.Offset(rowCount, 0)
   count = 0
   totalSum = 0
   totalProd = 1


   Do
      count = count + 1
      totalSum = totalSum + ActiveCell.Offset(rowCount, 1).Value

      On Error Resume Next
         totalProd = totalProd * ActiveCell.Offset(rowCount, 1).Value

      rowCount = rowCount + 1
   Loop While ActiveCell.Offset(rowCount, 0) = stationID



   invCount = 1 / count

   ActiveCell.Offset(stationCount, 3).Value = stationID
   ActiveCell.Offset(stationCount, 4).Value = count
   ActiveCell.Offset(stationCount, 5).Value = invCount
   ActiveCell.Offset(stationCount, 6).Value = totalSum
   ActiveCell.Offset(stationCount, 7).Value = totalProd

   stationCount = stationCount + 1
   Loop
End Sub

Sub CallGeoMean()
Dim count As Integer
```

```
Dim product As Double
For count = 0 To 3

   product = productGeo(ActiveCell.Offset(count, 0).Value)

   ActiveCell.Offset(count, 2) = product
Next count

End Sub
Private Sub GeoMean()
   Dim i, rowCount As Integer
   Dim stationID As Integer
   Dim product As Double
   Dim indicator As Boolean

   'ActiveCell = myPointer

   product = 1
   i = 0
   indicator = False

   stationID = ActiveCell.Value

   If ActiveCell.Offset(i, -3).Value = stationID Then
      indicator = True
   Else
      Do Until ActiveCell.Offset(i, -3).Value = stationID
         i = i + 1
         indicator = True
      Loop
   End If

   If indicator = True Then
      Do While ActiveCell.Offset(i, -3).Value = stationID
            product = ActiveCell.Offset(i, -2).Value * product
            i = i + 1
      Loop
   End If


   ActiveCell.Offset(0, 2) = product
   MsgBox "Product is: " & product


End Sub
Private Function productGeo(stationID As Integer) As Double
   Dim i As Integer
```

```
    'Dim stationID As Integer
    Dim product As Double
    Dim indicator As Boolean

    MsgBox "Station ID: " & stationID

    product = 1
    i = 0
    indicator = False

    If ActiveCell.Offset(i, -3).Value = stationID Then
       indicator = True
    Else
       Do Until ActiveCell.Offset(i, -3).Value = stationID
          i = i + 1
          indicator = True
       Loop
    End If

    If indicator = True Then
       Do While ActiveCell.Offset(i, -3).Value = stationID
             product = ActiveCell.Offset(i, -2).Value * product
             i = i + 1
       Loop
    End If

    productGeo = product

End Function
```

Visual Basic script for ArcGIS to compute Median value of fecal coliform dataset at each monitoring station (Courtesy: Venkatesh Merwade):

```
Option Explicit
'Private err As Label

Private Sub Median()
 Dim pMx As IMxDocument
 Set pMx = ThisDocument
 Dim pTable As ITable
 Set pTable = FindTableByName("FC_data_7")
 Dim pRow As IRow
 Dim pCursor As ICursor
 Set pCursor = pTable.Search(Nothing, False)

 Dim Count As Long
 Count = pTable.RowCount(Nothing)

 Dim i As Long
 Dim StationID() As Long
 ReDim StationID(Count)

 StationID(0) = pTable.GetRow(i).Value(4)
 Dim j As Long


 j = 1
 Open "c:\temp\fc_data_07.txt" For Output As #1

 For i = 1 To Count - 1
  If pTable.GetRow(i).Value(4) <> StationID(j - 1) Then
   StationID(j) = pTable.GetRow(i).Value(4)
   j = j + 1
  End If
 Next i

 Dim Value() As Long
 'ReDim Value(1 To 5000)
 Dim StatID As Long
 Dim k As Long
 Dim q As Long
 'q = 0
 Dim Med As Double
```

```
For i = 0 To j - 1
StatID = StationID(i)
'MsgBox StatID

  q = 1

  For k = 0 To Count - 1
    If pTable.GetRow(k).Value(4) = StatID Then
      ReDim Preserve Value(1 To q)
      Value(q) = pTable.GetRow(k).Value(3)
      q = q + 1
    End If
  Next k

  ShellSort Value


  Dim m As Long


  Med = FindMedian(Value)


  'MsgBox "statid is: " & StatID & " and median is " & Med, , "median"
  Print #1, StatID & ", " & UBound(Value) & "," & Med

Next i

 Close #1

 MsgBox "done"


End Sub

Private Function FindTableByName(inString As String) As ITable
On Error GoTo ErrorHandler
  Dim pMxDocument As IMxDocument
  Dim pMap As IMap
  Set pMxDocument = ThisDocument

  Set pMap = pMxDocument.FocusMap

  ' Get the table named XYSample.txt
  Dim pStTabCol As IStandaloneTableCollection
  Dim pStandaloneTable As IStandaloneTable
  Dim intCount As Integer
```

```
  Dim pTable As ITable
  Set pStTabCol = pMap
  For intCount = 0 To pStTabCol.StandaloneTableCount - 1
    Set pStandaloneTable = pStTabCol.StandaloneTable(intCount)
    If pStandaloneTable.Name = inString Then
      Set FindTableByName = pStandaloneTable.Table
      Exit For
    End If
  Next

  Exit Function
ErrorHandler:
  MsgBox "FindTableByName - " & err.Description
End Function

Private Function FindMedian(Nums() As Long) As Double
  'MsgBox count, , "count"
  'MsgBox count Mod 2, , "mod"
  Dim Count As Long
  Count = UBound(Nums)
  'MsgBox Count, , "nums"


  On Error GoTo err

  If Count = 2 Then
    FindMedian = (Nums(1) + Nums(2)) / 2
    Exit Function
  End If

  If Count Mod 2 = 0 Then
    FindMedian = (Nums((Count / 2) - 1) + Nums((Count / 2))) / 2
  Else
    FindMedian = Nums((Count + 1) / 2)



  End If
Exit Function
err:
MsgBox "findmedian", , Count

End Function

' shell sort

Public Sub ShellSort(ByRef A() As Long)
```

```
 Dim Lb As Long
 Dim Ub As Long
 Lb = LBound(A)
 Ub = UBound(A)

    Dim n As Long
    Dim h As Long
    Dim i As Long
    Dim j As Long
    Dim t As Variant

    ' sort array[lb..ub]

    ' compute largest increment
    n = Ub - Lb + 1
    h = 1
    If (n < 14) Then
        h = 1
    Else
        Do While h < n
            h = 3 * h + 1
        Loop
        h = h \ 3
        h = h \ 3
    End If

    Do While h > 0
        ' sort by insertion in increments of h
        For i = Lb + h To Ub
            t = A(i)
            For j = i - h To Lb Step -h
                If A(j) <= t Then Exit For
                A(j + h) = A(j)
            Next j
            A(j + h) = t
        Next i
        h = h \ 3
    Loop
End Sub
```

Appendix F: Non-Point Loadings from Upstream Segments

Table F.1: Decayed Non-Point Loadings from Each Upstream Watershed Segment

(Retention time in Lake Houston accounted for)

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	JunctionID (HydroID of Outlet Junction)	Down-stream Length (km)	Flow (m^3/sec)	Velocity (m/sec)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay
701	667.4	2.56E+08	6.48E+15	1684	62.3	15.20	0.46	1.57	6.2E+14	91%
702	1291.0	4.68E+08	6.47E+15	1682	0.0	30.05	0.58	0.00	6.5E+15	0%
704	574.0	2.24E+08	1.30E+16	1685	74.2	7.09	0.36	2.40	3.5E+14	97%
801	1024.7	3.52E+08	6.99E+15	1683	0.0	33.77	2.62	0.00	7.0E+15	0%
802	2322.9	7.13E+08	1.13E+16	1671	55.1	22.61	2.62	0.24	7.8E+15	31%
901	143.0	4.68E+07	1.85E+15	1654	0.0	5.42	0.33	0.00	1.8E+15	0%
902	387.2	1.24E+08	3.01E+15	1668	28.8	3.94	0.29	1.13	5.5E+14	82%
1001	160.4	5.08E+07	1.81E+15	1666	18.8	61.77	0.54	0.40	9.9E+14	45%
1002	776.0	2.40E+08	6.17E+15	1669	47.1	60.16	0.53	31.60	1.6E-05	100%
1003	1012.5	2.82E+08	4.07E+15	2920	68.9	8.94	0.39	32.65	2.2E-06	100%
1004	570.1	1.56E+08	6.42E+15	1620	75.4	20.06	0.50	32.31	5.7E-06	100%
1005	45.2	1.45E+07	6.54E+14	1655	0.0	85.22	0.59	0.00	6.5E+14	0%
1006	361.2	1.08E+08	1.04E+16	1665	15.7	22.36	0.52	0.35	6.1E+15	41%
1007	759.6	2.12E+08	2.91E+16	1663	25.8	18.93	0.49	0.60	1.2E+16	60%
1008	1133.4	2.69E+08	7.62E+15	1618	75.3	34.90	0.61	32.02	1.1E-05	100%
1009	842.5	1.99E+08	8.27E+15	1611	80.4	6.31	0.34	33.29	1.7E-06	100%
1010	558.0	1.56E+08	4.41E+15	1672	68.9	8.70	0.38	32.67	2.3E-06	100%

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	JunctionID (HydroID of Outlet Junction)	Down-stream Length (km)	Flow (m^3/sec)	Velocity (m/sec)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay
1011	404.3	1.18E+08	2.32E+15	1624	74.8	3.76	0.29	33.57	3.2E-07	100%
1012	1160.0	2.77E+08	4.96E+15	1595	138.7	8.79	0.38	34.76	1.1E-07	100%
1013	12.2	3.52E+06	7.12E+14	1606	48.0	9.34	0.39	1.42	8.5E+13	88%
1014	917.5	2.13E+08	1.14E+16	1604	55.7	6.76	0.35	1.83	7.3E+14	94%
1015	852.9	1.99E+08	3.44E+15	1626	120.7	6.32	0.34	34.64	9.3E-08	100%
1016	330.7	9.07E+07	5.27E+15	1610	44.7	2.87	0.27	1.95	2.8E+14	95%
1017	289.9	7.77E+07	9.29E+15	1608	51.4	2.47	0.25	2.36	2.7E+14	97%
1101	140.4	4.26E+07	2.35E+15	1646	7.4	4.07	0.30	0.29	1.5E+15	35%
1102	289.5	8.57E+07	4.60E+15	1644	28.1	2.72	0.26	1.25	7.1E+14	85%
1103	185.4	5.66E+07	2.47E+15	1642	0.0	2.50	0.25	0.00	2.5E+15	0%
1104	73.5	2.21E+07	6.49E+14	1638	23.9	0.70	0.17	1.66	5.4E+13	92%
1105	580.8	2.00E+08	5.40E+15	2978	5.2	6.34	0.34	0.17	4.2E+15	23%
1107	113.6	3.67E+07	1.07E+15	1634	0.0	3.97	0.29	0.00	1.1E+15	0%
1108	306.2	8.83E+07	2.30E+15	1600	20.3	2.80	0.26	0.89	6.0E+14	74%
1113	189.5	5.93E+07	5.10E+15	1649	6.1	1.88	0.23	0.31	3.2E+15	37%
2425	76.2	2.39E+07	1.34E+15	1648	0.4	6.71	0.35	0.01	1.3E+15	2%
2426	91.6	2.99E+07	1.96E+15	1656	0.0	1.01	0.19	0.00	2.0E+15	0%
2427	19.2	6.17E+06	2.08E+14	1659	5.7	0.20	0.11	0.61	8.4E+13	60%
2428	6.0	1.94E+06	1.34E+14	1660	5.5	0.06	0.07	0.85	3.8E+13	72%
2429	13.2	4.25E+06	2.86E+14	2984	9.5	0.39	0.14	0.80	8.6E+13	70%
2430	25.1	8.17E+06	6.37E+14	1664	11.3	0.26	0.12	1.09	1.2E+14	81%
2431	77.5	2.33E+07	1.32E+15	1640	3.1	0.74	0.17	0.21	9.6E+14	27%
2433	75.8	2.49E+07	4.96E+14	1633	0.0	7.13	0.36	0.00	5.0E+14	0%
2434	36.6	1.10E+07	8.81E+12	1616	0.0	1.18	0.20	0.00	8.8E+12	0%
2435	77.7	2.61E+07	1.46E+14	1631	11.4	0.83	0.18	0.75	4.8E+13	67%

Watershed Segment	Area of Watershed (km^2)	Runoff (m^3/yr)	Annual Load (cfu/yr)	JunctionID (HydroID of Outlet Junction)	Down-stream Length (km)	Flow (m^3/sec)	Velocity (m/sec)	Travel Time (day)	Decayed Load (cfu/yr)	Percent Decay
2436	4.5	1.43E+06	4.54E+13	1657	1.1	0.05	0.07	0.19	3.4E+13	25%
2437	14.7	4.13E+06	3.31E+14	1636	0.4	0.13	0.10	0.05	3.1E+14	7%
2438	3.9	1.24E+06	2.57E+13	1651	0.0	0.04	0.06	0.00	2.6E+13	0%

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